TÜRKİYE CUMHURİYETİ'NİN YÜZÜNCÜ YILI

Maden Mühendisliğinde Farklı Olgular ve Yaklaşım Yöntemleri

Editör

Çetin Yeşilova

BİDGE

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İçindekiler

CHAPTER I

Stability of the rocks; their time-dependent behaviour concerns

Mehmet Kemal GOKAY[1]

1. Introduction

Time-dependent behaviours of the rocks and stability cases for the openings excavated in them are considered here in a conceptual manner. Strength of rock materials and rock masses are advised to be tested through ISRM (International Society for Rock Mechanics) recomments. When the durations of these tests are considered, they can not be compared to the actual stress-strain conditions & behaviours of in-situ rock conditions. Engineering projects in/on earth crust which consist of mainly rock masses have developed to use for a long period of time. Projects including bridges, dams, urban buildings, tunnels, underground depots etc. have their surface and underground excavations which have been realised to serve for a long-time. The time considered in some engineered projects could

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be as long as 100K or 1000K years like the ones for radioactive waste related underground depositories. The other most common underground structures like; metro tunnels, rail-road tunnels, underground shelters, passageways, other urban underground spaces, are usually excavated also to be used for long-time periods (i.e: more than 50 or100 years). All the decision considerations in these underground projects should then cover the risks related to their long periods of usages. Thus, they need to be designed, engineered, excavated, and operated accordingly. However, collected engineered data including mechanical property tests have their contradictions when the time is under consideration. Because almost all of the laboratory tests in rock mechanics are performed in rather short-time periods. That means engineers are under decision circumstances where they have to decide and operate their jobs by using the input data tested in short test duration. Disadvantages of these situations are not usually defined clearly in engineering related acts and legislations. The statements include “engineered, designed, projected according to latest developments, etc.” protype catchphrases are commonly used for new projects. However, when the actual decision conditions are considered, the risks over the engineers who decide for engineering structures in/on rock masses by using laboratory/field test data are really high. These tests are performed according to standards and recommended testing methods but, their short test durations are obvious when they are compared with the actual life-times of the projected engineering works. Thus, the concept of time-dependent rock or rock-like material properties need to be considered in engineering designs and related legislative Acts. Otherwise, engineers are loaded with over responsibilities. Rock mechanics includes researches to predict physico-mechanical behaviours of rocks. Comparing strength properties of rocks together with the applied stresses in three dimensional, 3D, space conditions is the starting point of rock failures. Improvements in this research field, force the engineers to follow rock mechanics context in their decision analyses to understand their responsibilities & decision loads in their engineering duties, (testing, designing, excavating, supporting, monitoring, operating, etc.) more clearly.

When the time is in consideration to evaluate the rock mass stabilities (which include engineering structures), impacts observed on the rocks' behaviours under different load conditions (including constant load) need to be analysed carefully. When the 3D stress conditions around deep underground excavation are considered, stresses (loads) originating due to overburden layers might be stable, constant, for certain geological time periods as long as the tectonic stresses and overburden depths etc. stay unchanged. In the concept supplied through Mohr-Coulomb criteria, Mohr circle is defining applied two dimensional, 2D, stress conditions on a particular underground rock mass location. Mohr circle position obtained from the applied σx and σy stresses at Mohr-Coulomb criteria graphs states also the risk of failure according to supplied Mohr-Coulomb failure envelope, *[$\tau=c+\sigma.\tan(\phi)$), where; τ: shear stress level, c: cohesion value of the rock, σ: normal stress level, and ϕ:internal friction angle]*, of the rocks under consideration. Engineers who provide decisions in rock engineering projects would like to be sure about the Mohr circle positions with respect to the Mohr-Coulonb envelope which separates stable and failure zones in this graph. Changing the envelope angles and cohesion values cause the differentiation in Mohr-Coulomb failure envelope conditions which also redefines the strength characteristics of the rocks. Actually, changing the applied 3D stress values (levels) in time causes different loading conditions on rock masses and it has been researched through time-dependent strength evaluations.

Engineers dealing with the projects in/on rock masses know (as a common concept) that rock strength values can be differentiated according to rock types and applied stress & strain variations during the rock mechanics tests. It is well known and given by Hashiba & Fukui, (2015) also that "*rock strength increases with an increase in loading rate (loading-rate dependency), strain increases under constant stress (creep) and stress decreases under constant strain (relaxation)"*. These authors studied and supplied evaluations about the constant "n" representing the degree of time dependency. According to them "n" values are describing; "*slow crack growth due to stress corrosion, has been used to formulate the loading-rate dependency of strength (Sano, etal., 1981) and the relation between creep stress and lifetime (Wilkins 1981)*". The "n" values can be determined through the tests performed under constant loading rates, (Okubo & Nishimatsu, 1985). Hashiba & Fukui, (2015) supplied 102 "n" values obtained from 42 rock samples which were given in three groups of data sets, (*including 3 rock types related data tested by the authors, 11 rocks & rock-like materials' data listed by Okubo, etal., (2013), and 30 rocks related data supplied by different researchers)*. Hashiba & Fukui, (2015) noted that "*a smaller value of "n" represents a larger loading-rate dependency*". According to their results, (in listed 42 rock types); the smallest "n" value obtained from granite, and the largest "n" value acquired from sandstone rock were reported. They also reported that wet rock conditions supplied lower strength and "n" values with respect to the dry conditions. In the similar context, one of the earlier works provided by Kaiser & Morgenstern, (1981), focused on "*creep and time-dependent failure processes*". These processes are influencing the rock masses' mechanical behaviours naturally, and they are expected to influence the performances of engineering structures in rocks as well. These authors pointed out that "*rock masses have often been deformed extensively due to tectonic activity and have yielded beyond their peak strength*". According to them, during excavation of deep underground spaces in weak/strong rocks, "*overstressing may develop due to stress concentrations near the opening*". This situation actually increases the importance of 3D stress-strain interactions surrounding the cavities. Kaiser & Morgenstern, (1981), noted for the similar cases and they wrote that, "*It is important to understand the time-dependent post-peak strength behaviour for the design of structures in overstressed rock*". Their modelled work presented "*the relevance of the time-dependent post-failure behaviour*": *i)* in unconfined failures (like it is observed at rock slope stability), *ii)* progressive failures, and *iii)* confined failures (observed at; underground excavations).

Time influences which cause strength differentiations are usually mentioned for the sedimented rocks including clay and salt layerings. Paraskevopoulou, (2016), wrote that "*time-dependent behaviour is most commonly associated with primarily clay-rich, argillaceous, or salt rich rock materials that exhibit creep deformations".* She added that this concept was discussed also by Cidivini, etal., (1979) and Ottosen, (1986). She listed also information about the "*strength reduction*", circumstances perceived in brittle rocks together with the related studies like; Lajtai & Schmidtke, (1986); Malan, (1999); Diederichs, (2007); Damjanac & Fairhurst, (2010); Perras, etal., (2013); Paraskevopoulou, etal., (2015). Design and shift engineers working for excavation projects in/on earth crust have their attention that differentiation occurred in expected (determined through laboratory and field test data) rock mass strengths and 3D induced stress conditions around the excavation. Likewise, Zhao, etal., (2022) pointed out that high axial stresses formed due to projected engineering excavations in hard rocks cause "*significant rheological behaviours that can lead to long-term instability*". According to these authors, initial damages caused by excavation influence long-term mechanical behaviour of the deep rock mass. They wrote also that "*for rock mass with high integrity after excavation, the time-dependent cracking response of rock mass is poor and new cracks are almost no longer generated. For rock mass with poor integrity after excavation, stress concentration is caused and time-dependent cracking is obvious*". Through their studies they noted that; "*the time-dependent failure characteristics of intact granite in the pre-peak stage and fractured granite in the post-peak stage are different*". It is important here to research if similar time-dependent failure behaviours could be expected in other hard rocks.

Time-dependent behaviour studies performed to understand rocks' mechanical properties lead the engineers to evaluate their project cases in more real-world conditions. This type of evaluation must be conducted for all types of engineered structures in/on rock masses, because they are generally constructed for long-time period usage (around 10-100 years). Thus, following studies including researches on rocks' time-dependent properties including creep behaviours are then providing information to enhance the knowledge and experiences in the concept; Lajtai, (1991), Ozgenoglu, (1998), Cetin & Ozgenoglu, (2005), Ding, etal., (2020), Zhao, etal., (2021), Zhang, etal., (2021), Innocente, etal., (2021), Frenelus, etal., (2021), Frenelus, etal., (2022), Tarifard, etal., (2022), Hou, etal., (2023), Liu & Zhang, (2024), etc. Time-dependent rock strength differentiation has significant effects on engineering projects. Stability risk encountered due to time-dependent rock strength changes should then be analysed carefully to ensure engineering structures' long-time health. In this context, study performed by Wang, etal., (2024) could also be taken into account. They pointed out the potential instability conditions for underground structures originated from creep related inelastic deformation in the rock masses surrounding these spaces. In general, in-situ rocks are loaded in 3D with varying stress conditions. Therefore, while supplying decisions, engineers should consider time-dependent strength characteristics of the rock masses as well. Wang, etal., (2024) warned about *"accurate characterisation of the creep behaviour"* related to the rock masses surrounding the underground structures like radwaste repositories. They worked on long-term mechanical properties of granite rock specimens through the rock creep tests. Their works included various test variables which could be observed around the projected caverns in hard rocks like; fracture inclinations, stress conditions, temperatures, and water content. They concluded that "*the temperature had a limited effect on the creep behaviour"* of the granite rocks in the range *"designed for the disposal repository*". They added also that, the other test variables, (rock fracture angles, axial stress values, and water saturation levels), they researched on "*significantly modulate both the creep strain and creep strain rate in granite*". They forwarded that, "*under similar axial stress conditions*", saturated rock specimens showed different failure times (durations) than the dry specimens and they pointed that "*more* *attention should be paid to the time-dependent characteristics of surrounding rock containing steep dip fractures under high saturation conditions after the excavation stress redistribution*". Engineering considerations in time-dependent parameters of rocks have been supplied through the researchers who realise these parameters' influences in various degrees on the projects in/on rock masses. One of them was reported by Zhang, etal., (2015). They concentrated on the creep behaviour of clastic rocks in their studies related to the Xiangjiaba (China) hydropower project. They wrote that clastic rock was "*the main media of the fracture zones"* and it was reported that it had poor physical and mechanical properties. The authors supplied their evaluation on clastic rocks that their creep behaviour is not noteworthy at low deviatoric stress. According to them, "*the creep behaviour is very significant and time-dependent deformation is large"* for these rock types at high deviatoric stress conditions. Then they pointed; "l*ess creep of the rock sample may occur at high confining pressure*".

2. Re-evaluation of rock strength data by including time effects

Evaluations of rock materials and rock masses property differentiations have provided outputs and they have been getting enhanced to reach actual real-world mechanical behaviour coverages of the rocks. Introducing after the rock types and their micro context differentiations, mechanical property changes observed due to the rock material and rock mass differences is a common research area in rock mechanics. Failure criteria, rock mass rating procedures, and 3D discontinuity analyses have been captured by researchers for their developments. Improving digital computational methodologies have introduced 3D modelling of discontinuities and numerical modelling have encapsulated 3D stress-strain and fracture modelling for surface/underground spaces in their design stages. Integrating engineering steps of excavation methods in mining and civil engineering operations with their rock mechanics analyses in engineering decisions help detailly to the decision makers. Stability survey for the designed structures and their risk assessments are fulfilled by using rock mechanics subjects. Actually, the basic background of these analyses are based on the input data collections and determination of rock behaviours. Engineers responsible for designs and operational shift duties are evaluating the collected input data for their decisions in mining and civil engineering related excavation projects. The logical contradictions encountered in these procedures are related to the time-dependent behaviours of rocks and soils. Engineers should not forget that all the input data obtained from field observations, in-situ tests, and laboratory tests are performed in certain tests & observation durations. These are a few months or years for field observations, and a few minutes for laboratory tests. On the contrary, decisions supplied by engineers influence the whole service life of the surface/underground excavations. Time-dependent effects on the induced stresses and rock/soil strengths should then be tried to be evaluated through the available, time-dependent associated tests and analysis methods. In addition to these setbacks, there is another obstacle in rock related decisions. That is the uncertain characteristics of input data. Decisions supplied by engineers are their professional outputs and cover their education, practices and experiences. The data collected for engineering projects and then used in different stages of excavations and constructions actually have their uncertainties in rock mechanics context. Beside the natural uncertain facts (like; continuity of discontinuities, accepting the test results obtained from drilling carrots samples for the whole rock masses, etc.) there are also calculation based acceptances like; mathematical averaging, covergences, standard deviation values, and the other statistical analysis outputs. These data obtained from the tests, in fact, have their own probabilistic characters in addition to the obstacles encountered for the testing specimens, equipment, and instruments including factors like; electronic sensors, climatic factors, temperature, mechanical attachments, human errors etc. Similar factors influence most of the collected input data values which can be accepted as the causes of the differentiation in test values from the real-world values of the rock properties which engineers try to measure. Some of these obstacle factors have already been known and certain logical approaches (acceptances) are facilitated in standard test procedures. Test results have always been handled with some questions in mind. What is the level of differences between the results provided by the tests and the actual properties of the rocks in-situ? Technology used in the testing methods have been getting improved and these improvements cause to obtain more realistic rock properties through the tests. Facilitating the test outputs obtained from; electrical earth resistivity, magnetic susceptibility, electro-magnetic wave differentiations, microgravity, etc. might supply hints for engineers to estimate rock mechanical properties. These subjects need to be developed to decrease uncertainty cases in rock/soil mass related decisions. For instance; underground spaces which have been used for general public services have to be under control for their stability. Especially metro tunnels which are in use for a large number of people. Engineers providing decisions for these structure-related; designs, excavations, supports, constructions, monitoring, operations, etc. should then be aware of the factors mentioned above including the uncertain characteristics of the rock/soil strength properties.

For instance, the study performed for the Seoul (S.Korea) metro system as a stability monitoring system, (Chung, etal., 2006), has hints about the measurement, monitoring, data transferring, data saving, and data analysis & evaluation in continuous manners. The monitored values in this study included "*earth pressure, pore water pressure, rock bolt axial force, concrete and reinforcing bar strains",* in addition to tunnel convergence measurements. Authors wrote that "*the long-term behaviors of the ground around tunnels"* are also in control together with any stress differentiations occured at the tunnel lining system. Like the study mentioned for the Seoul metro system, continuous monitoring of the induced stress levels at different positions surrounding the lined metro tunnels provides 3D stress differentiation in time. Comparing them with strength values of rock masses in 2D or 3D rock failure approaches could provide the possible problematic risks in stabilities. The data obtained in time can also be used to understand time-dependent behaviours of the rock masses around the tunnels.

Rock masses are different from soils due to their cemented structures. Rock masses demonstrate different mechanical behaviours according to their origins and structures. They could present weak and hard strength characteristics (fiziko-mechanical properties) including different elastic modulus, Poisson's ratios, uniaxial & triaxial strength values, toughnesses, specific gravities etc. in basic. Weak rocks are more ready to lose their compactness due to applied 3D stresses. Then they are usually more open for weathering procedures. Some rocks even have high permeability values for circulating natural liquids (groundwater, oils, etc.) and gasses (magmatic gasses, organic gasses). Paraskevopoulou, (2016), wrote about the weak rocks (DIN 4022 T1, and ASTDM 4644), which break aparts in short periods of time even with the effects of climatic effects. She noted; ISRM (1981), Clerici (1992), and Klein (2001) for their *"approach to define weak rocks based on the Uniaxial Compressive Strength*" properties. Other researchers in rock mechanics have their soil, weak & hard rocks definitions as well. When the researchers and engineers realised that, there should have been other factors influencing the rock strengths like their weaknesses, rock mass classification systems have then been offered to point their "differences". Discontinuities and their influences on the stabilities of surrounding rock masses around the excavations can also be analysed through available approaches. Since the excavations (as metro tunnels, shelters, depots, highway slopes, etc.) are going to be in service for a long-time period, differentiation in mechanical behaviours which will be encountered at surrounding rock masses would like to be predicted as well. Engineers who work for the stability monitoring office of a metro tunnel for example should also be sure about the effects of induced 3D stresses which could have time-dependent fluctuation as well. Time-dependent property changes of rocks were studied for tunnelling also by Paraskevopoulou, (2016). She proposed that these changes can be the outputs of "*different mechanisms depending on the rock type*". Rocks' mechanical behaviours under long-time loading conditions have been explained by creep and stress relaxation.

When the earth crust is under consideration, due to earth's gravity, rock masses positioned as part of the crust have their own weights which forms the primary in-situ 3D stress field in the ground. The other outside factors (i.e.; temperature, climatic impacts etc.) are also effective on rock masses' mechanical behaviours. Considering the rock masses around an orebody positioned 2000m depth in earth crust, may cause engineers to visualise the long-time influences of 3D induced stress conditions through geological eras (time considered here may be defined in millions of years). The question engineers should ask in their projects is, if the strength of this country rocks (positioned at 2000m in depth) are similar to the exactly similar rocks positioned in shallow depth (i.e; 100m)? This type of engineering consideration which covers knowledge and experiences of different professions and rock mechanics context push further research studies to understand time-dependent influences. As Paraskevopoulou, (2016) stated "*incorrectly integrating*" time-dependent properties of rock masses, "*or in the worst case neglecting them, can yield incorrect results that could lead to overestimating or even underestimating the support measures applied, impacting the construction"* which may cause instabilities at the projected excavations or even cause accidents.

Actually, if there is no negative outcome related to surface & underground structures' stabilities, usages of these structures have continued without any quarrels. However, when an event, accident, including fatalities happens at these structures, legal disputes have included all stages of these structures, starting from their design concepts to their monitoring & operational periods. The data covering all the phases of their designing, constructions, monitoring, and operation periods could then be asked formally to be re-analysed in these kinds of investigations. However, accepting the engineering "decision parameters" related to surface & underground structures are descriptive in full-scale is not a realistic concept. Engineers have supplied their decisions to form these structures, constructions, with their experiences to cover uncertainties. The results of these decisions sometimes have severe legal issues in case of accidents and disastrous events. For instance, when the city buildings collapse in an earthquake, design and shift engineers are asked to provide their reasoning about the developed collapses in these buildings even after 20-30 years of their constructions. Similarly, collapses of underground mine galleries or metro tunnels have their long legal disputes covering engineering design & operational activities. In these surface and underground disastrous cases, societies would like to find the actual reasons for the accidents. Supplying engineering decisions for surface & underground structures by analysing collected input data (which include a certain degree of uncertainties) forces the engineers currently to define the risk of instabilities. Actually stability performances of these structures should not be supplied through sharp decision sentences including words like; "stable" or "instable". Engineers should follow legislative rules, standard tests, and recommended engineered risk analyses (i.e.; Eurocode7) to include uncertain conditions as well. Similar engineered decision approaches push the nations' legal authorities and the members of nations to accept the natural risks of failure cases. That means, there is no surface & underground structure in/on earth crust without risk of failure. However, engineers should carry out all possible analyses to cover & report these instability cases by using all available rock & soil mechanics related approaches.

The stability of the surrounding rock masses of underground spaces for instance have been analysed for their expected 3D induced stresses. Beside the earthquake and ground vibration considerations, induced stresses are monitored in certain positions at some of the engineering projects. Actually, induced stresses in rock masses are expected to be differentiated in time due to surrounding natural and human related events. Natural influencing event groups include mainly; gravity, quakes, tectonic stress variations, void & crack initiations, fracture propagations, rock weathering, groundwater level differentiations, etc. Similarly, human related influences are generally related to man-made excavations, surface constructions, and other man-made vibration sources. When the surface excavations (performed for foundations, railways, highways, open pit mines and quarries, etc.) are listed with all the underground man-made excavations (realised for mining & civil engineering purposes) throughout the world, the disruption on the induced stresses in the rock masses can be realised. Thus, in the long-period time scale, any types of cavities, spaces, and excavations which will be formed in/on rock masses (naturally or artificially as human activities) are candidates of disturbance-starters in available induced stress conditions. According to Kirsh (1898) approach, influencing stress zones (secondary stresses) have been formed around the excavations where the original (primary stresses) vertical & horizontal field stresses are changed into radial and tangential stresses. When the time is handled at the nanoscale level, time required in changing the induced stress directions in similar influence zones can be researched for different rock masses for their responding gap to understand any further differences leading to instabilities. In actual world conditions, it is rare to come across massive and uniform rock masses, thus forming a circular space in a rock mass which have their discontinuities and defects zones in micro & macro scale is logically different from the conditions given in Kirsch approach. Induced stresses as differentiated into radial-tangential directions, they supply different stress concentration options to overcome the strength of the rock masses when they are compared to the earlier primary orginal stress field. Therefore, engineers should be ready to analyse the influences of these new stress conditions without forgetting their differentiation characteristics in long-time periods. Underground spaces like mine galleries, urban tunnels, shelters, depositories, etc. can be designed in different geometric shapes and sizes. Induced stress redistribution just after their excavations and their differentiation in time (due to surrounding engineering activities like; rock blasting, excavating neighbourhood underground spaces, etc.) are important design concepts to be evaluated. Engineers in surface & underground excavation projects need to be informed about already existing and planned surface & underground excavations to evaluate their immediate and long-time interactions on their projects according to available analyses. In basic conditions, approaches presented by Kirsch (for homogeneous materials) and Terzaghi (1946), (for rock masses) defined disturbance (influence) zones around excavations. Terzaghi's "rock load height" concept presents the changing of this height with the types of rock masses. Changing the strength and behaviour types of rock masses then influences the defined height values directly. Induced stresses and the causes of rock weathering parameters affects the rock masses' behaviours. Moreover, rock masses surrounding the underground excavations have their potential to present time-dependent rock strength characteristics. Therefore, engineers need to control these rock masses' creep, fatigue, stress-relaxation, etc. type behaviors as well.

Main sources of field stresses at certain locations in/on earth crust originate due to (mainly) gravity and tectonic activities. Thus rock masses have compressed by their weights through the geological eras and form their primary 3D stress conditions which are still in reshaping (differentiation) stages. When the excavation is realised on the earth crust induced stresses formed similar to underground excavations. Since there is no overburdened layer left over the surface excavations, they are designed by taking account of their sidewalls' (slopes) and floor layers' (foundations) stabilities. As the surface excavation is getting deeper to reach its final designed stage, induced stresses applied to their slopes and foundations are increased as well. Surface excavation for small scale foundations may take several days or months to finish. But large scale dams or especially open pit mines require years of rock blasting and related operations to reach its deepest planned layer. When the time of excavation is considered, induced horizontal stresses are getting higher as the depth of the excavation increases in stepwise manner. That means, rock masses located at particular slope positions of the surface excavations are loaded increasingly in stepwise mode. Each new bench excavation realised in downward direction increases the 3D loading conditions at these slopes. In other words, induced stresses at the slopes of surface excavations have their repeated increments (differentiation) when the new bench level is excavated downwards. In design stages, engineers are also required to think about the weathering influences of rock masses at surface excavations beside the rock masses' time-related behaviours. Rock mass weathering and rocks' time-related influences have their uncertainties due to the rock mass structure properties. Considering 3D stress fluctuation in time, (as the surface excavations are progressed), is an important decision parameter. Fracture initiations and their propagations with the existing discontinuity sets are forming slope stability problems which should also be monitored for a long-time period. Time-dependent behaviours of the rock masses at surface excavations are also analysed for their stability cases together with loading-rate differentiation circumstances. In engineered manufacturing practice, it is very difficult to produce solid materials without micro/nano voids & fissures. Similarly, it is accepted in engineering that all types of rock materials have their nano/micro, voids & fissures. Porosity properties of rock masses are the hints of these voids in their structures. In solid mechanics, it is also known that if there are voids & fissures in a solid mass, applied outside stresses cause fracture propagations in these rock masses according to their toughness properties. Strength characteristics of the rock bridges among micro/nano scale (fissures, voids etc.) fractures play an important role on time-dependent behaviours of the rock masses. Engineers also need to evaluate factors influencing rock fracture mechanics by taking following parameters into consideration; fracture toughness, energy storage capacities, elastic modules, mineral & matrix combinations of the rock materials, weakness zones in the rock masses, etc.

3. Influences on the compactness of rocks in time

When the types of rock under consideration, magmatic, sedimentary and metamorphic rock types formed in different time periods of earth crust genesis through geological eras. In a conceptual point, magmatic rock formations, sedimentation procedures and metaformic processes have continued since at the beginning of the earth crust genesis. When a hypothetical rock specimen is isolated and it was thought as "a separate mass" in space, factors influencing this mass's stability can then be considered in a conceptual manner. The questions might be asked here; "*What can be the disturbing influences on the isolated rock specimen in space* *which cause it to breakdown*". The outside influencers in such a hypothetical condition can be listed theoretically as; a) material (*solid, liquid, gas, etc.)* impacts on the specimens, and b) energy (*heat, sound, vibration, light, magnetism, electron, gravity, radioactive particles (α, β, λ), etc.*) impacts on the specimen. It should be borne in mind also that these impacts might have included the effects originated due to the different types of material phases and energy types (*which have influenced the selected specimen' compactness but they can not be recognised or they are not known (explored) yet*). When the time periods are considered, these impacts could be realised in a short or long period of time. When the engineering projects are constructed in/on rock masses for a long-time period, their stabilities need to be evaluated by taking care of time-dependent induced stresses & rock behaviours conditions.

Research on the rock samples which are either loaded in different loading rates, or keep different levels of 3D stresses stable (constant) for selected periods of time influence the strength characteristics of solid rock properties. These two loading procedures basically include their time related influences on the solid materials and rock samples. Satheesh, etal., (2024) for instance worked on time-dependent behaviour of caverns excavated in rock salt and shale by using numerical analysis. They pointed to the importance of the long-time strength behaviours of the rock masses which include underground caverns. Time-dependent differentiation in mechanical behaviours of rocks like "creep",influence the stability consideration of underground structures. They pointed out that this time-dependent rock mechanism "*plays a significant role in such designs but is often overlooked*". They presented the results obtained from their finite element analysis through performed parametric studies concerning these caverns to understand the long-term behaviours by evaluating the influences of depths, shapes, volumes, and time. Due to population increase in countries, usages of underground urban spaces are getting increased and their stabilities are concerning more deeply because of their locations under populated city limits. Instabilities caused by them influence more people if they are metro tunnels (or: underground car parks, sport-cultural-social centres, shelter, depots, etc.) under the city limits. Thus, surface and underground excavations considered through their short or long time stability performances are always main engineering concerns in societies.

4. Strength differentiation due to long-time loading conditions at engineering structures.

Engineered structures like; underground metro tunnels, mine galleries, shelters, depots, dams, bridges, skyscrapers, buildings etc. are constructed as stable to provide secure and healthy services for their engineered structure purposes. Damjanac & Fairhurst (2010) wrote that mechanical responses of rocks to the applied loads are controlled by mainly "*two scale factors; size and time*". These authors mentioned the studies of Einstein & Meyer, (1999) which included the time effect on the strength and deformation of the rocks. These parameters are very important when underground radwaste depositories are under consideration in rock masses. Because the depots should have kept their stable circumstances for a very long-time to isolate the radioactive waste "from the biosphere for the order of a million years". Damjanac & Fairhurst (2010) studied the strength conditions of the rock masses around the underground nuclear waste repositories (400-700m depth, influencing temperature is less than 100 degrees Celsius) to understand the questions arose; "*Will the strength decline essentially to zero after such extended periods or does the rock have a non-zero ultimate strength or 'threshold' that can be considered time independent, for the time-scale of interest*?".

Engineering constructions have been time consuming projects which require a certain degree of budget to realise. Therefore, bridges, dams, highways, tunnels, underground depots, shelters, urban underground spaces, etc. are all constructed for long-time periods. Long-period of servicing time expectation for surface & underground structures force researchers to understand time-dependent behaviours of rock masses. Hashiba & Fukui, (2016) for example studied this behaviour for granites. In their review they listed 32 studies which had been performed between the years of 1962 and 2015 to understand time-dependency of the granite rocks. Beside the importance of the time-dependent studies on mechanical properties of rocks, performed research works are limited as these authors mentioned. Actually, authotories (including companies) dealing with surface & underground structures would like to evaluate the time-dependent mechanical behaviours of the rock masses related to their projects. Time-dependent rock strength behaviours have their impacts on the stabilities of the projected works. Thus, engineers would like to define their duties and responsibilities accordingly to supply good engineering services. Time dependent property changes have observed mainly through certain rock strength and rock property circumstances like; creep (deformation of rock masses under constant stresses), squeezing (time-dependent closure of the underground spaces), swelling (time-dependent volume increase in the rock mass), stress relaxation (time-dependent stress decrease while at least one principal strain is constrained and remains constant), Strength degradation (time-dependent strength loss chemically assisted and driven by stress corrosion), (Paraskevopoulou, (2016, 2017). Therefore, all these cases should be evaluated by design engineers of the projects and related data collection procedures must be diagnosed. Designing an engineering structure without taking into account the time-related stresses and strength differentiation in dynamic earth crust conditions, the resultant engineering decisions have their potential to supply signs of instabilities in time.

5. Conclusions

Stabilities of the surface and underground structures designed and constructed by engineering activities have their acceptance by societies and their legislative rules. There are obvious strength-related approaches which are used to compare 3D stresses applied on a solid material and its strength properties which are resisting them. Rock failure criteria are supplied and enhanced through different researches. Engineers have their hesitations when the subject is rock masses because of the uncertainties in their strength and structure properties. Discontinuity sets and their influences on the rock masses' strength properties are forming a branch of research subject in rock mechanics where the works are continued to understand 3D modelling of them and their influences. Obtaining the laboratory and in-situ test results in short testing time and evaluating the stabilities of engineered structures planned for long-time usages usually put the engineers' hesitations in their decisions. The researches performed in this context have been reviewed in this study to illustrate the knowledge & information obtained. Complexity of the subject is presented to the engineers qualified for different branches other than rock engineering to illustrate the stability decisions in rock engineering is not a state-forward job to be realised.

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CHAPTER II

Stability and safety concerns for underground museum spaces

Mehmet Kemal GOKAY[1]

1. Introduction

Museums have been organised to keep archaeological & historical artefact and remnants in safe and protective environments. Museums and their exhibitions are most probably organised in specially built surface structures. They can also be set to cover whole surface locations (sites) of an ancient town, a village or some parts of historic cities. In addition, especially important historic houses, or any other man-made surface structures can also be titled as protected structures to serve as cultural museums for the societies. These buildings might have basement levels as well. There are also some archaeological remnants where underground spaces are main parts of the declared museums. All the protected caves, dwellings, and

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underground spaces, (tunnels, passageways, shelters, cities, etc.), which are open for visitors as different types of museums should be well engineered for their stabilities and safeties. Thus, it is important to evaluate; if a sudden collapse at certain parts of underground museums have any possibility to happen while the people are visiting these museums. In the case of accidents, how are these people going to be rescued? There could possibly be several legal disputes in the aftermath of these unexpected events as well.

The parameters which should be considered for the stability of underground museum spaces could be similar to underground mine galleries. Therefore, stability cases of them can be analysed and evaluated, besides human related work & workplace accidents in them, through rock mechanics concepts. Professionals in the museum activities are aware of the emergency rules related to the visitors' safety and museum artefact protections. They should also be well aware of the structural stability of the surface and underground structures. There should not be an unmentioned, untouched, point in the definition of museum safety rules, (precautions), and responsibility distributions. Otherwise, if a historical surface building, (which could be organised for public services as a museum), collapses and includes fatal injuries of visitors & employees, what can be the reasons, explanations, evaluations, etc. of the collapse? It should not be forgotten that there are always "post-event inspections" after such accidents. Thus, official explanations are required to be prepared for further legal actions in the cases of underground museum space collapses. Thus, surface and underground museums which have different instability problems, are not suitable for public services. These types of museums might produce dangerous instable conditions for their visitors & employees. In fact, surface and underground structures which have been used as museums or any other public services might better to be evaluated regularly for their stabilities, (together with other related safety precautions & plans). The questions then should be asked to think about urban underground spaces', (museums, shelters, metro tunnels, shopping centres, caves, etc.), stabilities like; Who excavated these spaces? What were the rock excavation methods used? What were the supporting methods? How many years passed after the spaces were excavated? Is there any part of the urban underground space, (UUS), which had collapsed in those years? Who analysed the stability of them? Where the official reports were kept? Who was responsible for the control of underground museums' stabilities during their service, (usage periods)? Who is organising the safety rules & precautions for the museums, (surface & underground)? Who is keeping the official reports with full responsibilities? How are these reports' backups stored and maintained in time together with the related software used for the included analyses, graphics and texts? Currently, answers of these questions should be ready to handle, (in official manners), to surface and underground museum operations. Museums are thought of as common public locations so their stabilities and safeties require extra precautions. Due to the possible difficulties accessing museum halls in case of emergencies, (securing valuable archaeological, historical, remnants), rescue-team training for the museums are strict and tough procedures. In addition, dangerous events, (accidents), which happen in certain parts of the surface & underground museums have their potential to impact over the visitors' safety, (especially for underground museum visitors), in negative manners. Therefore, it is important to state that, all countries have to organise their ground engineering groups, (covers the engineers dealing with rock and soil mechanics; and other engineers & professionals in mining, civil, geology, geomechanics, architecture, city planning, software, and etc.), to monitor their public underground spaces like museums, metro stations, metro tunnels, shopping centres, carparks, etc. besides the stability assessments of surface museum buildings, structures. Absent of preliminary stability reports just before declaration of surface & underground museum facilities, and absent of monitoring activity reports for their stabilities; through surrounding rock masses for underground museums, foundation stabilities for surface museum structures, and their main construction body stabilities are real problematic situations for the directories of the museum organisations.

Historical work & workplace experiences in the mining industry gained through mine accidents & disasters have forced the nations to provide very strict mining safety Acts. Then, it is important to consider an answer here to the question; "Can we set similar strict applications for underground spaces, (Fig. 1), used for other urban purposes". Underground rock mass conditions could be different for mines, shelter, underground spaces, etc. but the necessities of their stabilities stay constant. Thus; spaces excavated for underground facilities should be planned and engineered through rock mechanics and other related engineered researches, (information, knowledge, experiences, etc.). In order to provide safe living, working, and visiting underground environments, engineers and other professionals must also be organised through directive legislative Acts. So responsibilities in underground space excavations and monitoring circumstances should then be well defined for all related counterparts in; projecting, funding, governing, contracting, consulting, designing, excavating, constructing, developments, utilisations, operations, monitoring, etc. circumstances. Underground space related morphologic features on

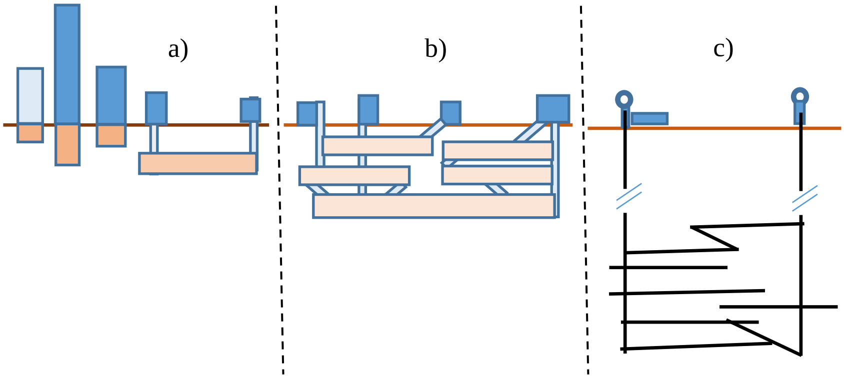


Figure 1. Underground spaces of surface & underground structures. a) Surface building with basements; underground shelters; UUS with separate access to ground surface. b) UUS like underground cities in Turkey and other countries. c) Underground mine structures for mineral or coal productions; abandoned of these mines could be developed as underground museums.

the ground surface are wide across in the world. Sinkholes for instance are a problem in some countries including the US and Turkey. Subsidence related to downward ground displacements are also an important aspect in regional plan considerations during master urban planning circumstances for historical & abandoned underground mine sites. Additionally, underground & surface excavations, UUS, metro tunnels have their influences on micro/macro scale ground displacements which should be studied to predict by different rock mechanics models while these underground spaces are still under their project periods. Their monitoring for their influences on ground displacements must also be engineered while these underground spaces are being excavated. Then the monitoring activities should be continued in their operation periods after their excavations & utilisations. All underground spaces must have officially “controlled” plans, (cover; permissions, control seals, dimensions, locations, test results for rock mass properties, rock behaviour models, support designs and predicted surrounding displacements, etc.), to estimate ground movements including alternative design options to decrease these displacements.

Actually, rock mechanics have influenced underground space designs gradually for the last 50 years. But, ground movements surrounding the mine galleries and other underground spaces had been predicted before by local experts, (engineers, foreman, workers, etc.). It is required to note that, there were years in history when high demands for the mineral and energy, (coal), products, (industrial development periods), reached peak levels due to economic & political conditions in the world’s economy. Mining history starts with the human existing, and some archaeological & historical mines have galleries which have not been managed to be mapped due to their collapse conditions. Similarly, some karstic cave systems have many cavities in branched manner, and they have not totally mapped also due to their harsh underground conditions. These obstructs in underground space localisation under the ground surface influence the predictions of subsidence effects of them. Induced displacements surrounding the underground spaces cause further instability problems for the surrounding rock masses and eventually for the surface civil purposed structures. Collapses occurring in the underground spaces influence the stress-strain distributions and groundwater conditions around them.

Environmental problems encountered due to the subsidence of underground mine exemplified by Longoni, etal., (2016) at Montevecchia marl mine in Northern Italy. These authors wrote about the high risk of collapses of underground spaces at the historic underground mines. They stated that "The high risk associated with subsurface voids, together with lack of knowledge of the geometric and geomechanical features of mining areas, makes abandoned underground mines one of the current challenges for countries with a long mining history". They analysed the problem in three main steps; Conceptualisation of the problem, (included conceptual modelling of; historical-geological-geophysical data, and miners' statements); Analysis of geometric features of underground openings, (numerical models to reach options of collapse possibilities); Supply risk and sensitivity features of collapsing conditions for abandoned underground mine spaces, (no collapse, minor collapse, and extensive collapse conditions). Since the input data have their uncertainties due to the features of rock masses around the underground mine openings, Longoni, etal., (2016) performed multiple scenarios to control their models.

The facts summarised above illustrate that surface and underground structures have their stability cases on the base of rock & soil mechanic concepts. When there is a plan to have a surface or underground museum, safety and security of the museums should also be considered with their stability cases as well. The visitors' and employees' safety should be considered for the extreme events which might happen at the planned museums. Especially underground museum concepts organised from abandoned underground mines, caves, historical shelters, underground passages, etc. are required to be well documented by projected steps which should be well described to get realising by groups of professions including engineers, architects, safety specialists, etc. Stability of these types of underground museums' spaces are important for their historic, archaeological, and natural values. Additionally, these spaces might in-house valuable archaeological, (historical), remnants as exhibition halls or museum depots. Therefore, unrequired museum disasters like fire, floods, explosions, earthquakes, human attacks etc. should also be considered with their impacts on the stability of the underground museum spaces. They may cause a decrease in surrounding rock mass strengths and some parts of the museum galleries might collapse with their values. Thus, any negative changes which have happened at the rock masses mechanical behaviours around underground museum spaces must be evaluated carefully to eliminate instability conditions to protect the museums assets.

2. Underground spaces as museum facilities

Museums have important items for nations' cultural, historical and archaeological background. There are many surface museums structures famous in the world due to their architectural features, and their artefact contents. These museums might have several basement levels or specially designed underground spaces to keep historical items in safe conditions. This is a common procedure for museums' artefacts to avoid all types of social unrest, climatic extremes, fires, etc. In some cases, underground spaces, (extra halls), for museum exhibitions are especially designed near the actual, (main), surface museum buildings, (usually subsurfaces of the museums' gardens and nearside roads have been used for these purposes). Karolidis, (2012), for instance compared the energy consumption of an underground museum, (The Roman Forum of Thessaloniki, Greece), and one surface museum, (in neighbouring locality), to evaluate their energy consumptions. The results supplied by him revealed that “a more stable exhibition environment is achieved at the Roman Forum Museum with less energy consumption and operating expenditure than in the ground-level museum”. The advantages in energy consumption should then be carefully engineered with the additional costs of extra safety precautions required for underground museums. Their stability and safety monitoring circumstances have to be covered in these types of comparison attempts.

In some cases, underground spaces are historical aspects to be protected as museums due to their archaeological values. There is also geopark definition, (protected parts of earth crust with their geological features), followed by countries to cover geologically important features as open-air museums, which some of them include underground spaces like; caves, cave networks, and sinkholes. In some other circumstances; historic underground cities like the one at Derinkuyu, (Nevsehir, Turkey), are well-known underground museum sites. These are museum organisations which have their underground spaces open for public visits. Similarly, some of the shelters prepared for nuclear war possibilities in the first half of the 20th Century have also developed in some countries as underground museum facilities as well. Ancient underground shelters had been excavated for similar safety & protection purposes against the climate impacts, harmful attacks of outsiders, and wild animals. There are numerous examples in the world, caves and man-made underground spaces have been used for similar sheltering and daily living purposes since early times of human history. For instance, Yamac (2018) listed eight archaeological shelters in the Tomarza, (Kayseri, Turkey), region. The Cappadocia region near

Kayseri city in central Turkey is famous with its ancient underground spaces, shelters, and underground cities. There are museums in this region for their surface and underground remnants. Kocalar, (2018a), wrote about the importance of historic underground cities in the Cappadocia region.

Underground museums all over the world are also well-known through their special features, Ragers, (2017), pointed out certain of these features by exemplifying underground museums in different countries. These museums are organised as the second usages of underground spaces which had been excavated earlier for different purposes like; underground mine, tunnels, cellar and docks. These are; Tirpitz museum, (Denmark); Salina Turda salt mine museum, (Romania); Centre for international light in an old storage cellar, (Germany); Underground catacombs, tunnels and unofficial arts spaces, (Paris, France).

For ancient civilisations, securing themselves from outsiders can be handled through; caves, castles with high & thick walls, and man-made underground rooms, (living circles), & passageways. Combination of passageways including living circles for 10K -20K people were planned and excavated at Derinkuyu, (Nevsehir-Turkey), mainly for similar purposes, (Kocalar, 2018b; Kultur portali, 2022). These underground cities have their underground galleries also for ventilation and waste material recharge purposes. They have their food storage depots for people and their animals as well. Most of the underground city rooms, passages and other various underground spaces have been untouched during centuries if their entrances were blocked. Since there is almost no documentation about their overall plans and design purposes, these underground spaces are found in later years by explorers, or come across at the foundations of engineering activities for modern urban city requirements, (infrastructure excavations, foundation drillings & excavations for surface structures). Countries which have such historical underground city spaces have their special museum organisations for cultural history purposes.

Conservation of archaeologically valuable underground city spaces, surface connections and their overall intactness are important issues for world cultural heritage points of view. If an underground city had been already known by local people but it has not been officially listed, (and conserved), in related government offices' documentations, it has been open for any possible damages by outsiders. Sometimes local people are using some parts of them for their domestic purposes like; depots, shelters for their products and animals etc. Kocalar, (2018b), wrote also that if explorations have not been realised in time for any other unrecovered underground city or underground shelter spaces, they are away from current adequate protection measures. That means they might gradually be demolished by nature itself. Most importantly, since some of the underground city galleries are not explored and documented yet, they might be partially damaged due to current urbanisation projects on the ground surface just over them.

Land ownership procedures for surface parcels and underground spaces interrelations should be settled down through legislative Acts describing procedures to define private underground spaces and protected locations for underground cities in 3D dimensions. Otherwise the underground museum concept is open for further dilemmas, (like the other UUS), as described by Gokay, (2023a). When the new planned underground spaces are under consideration for human requirements, (like; metro tunnels, food depots, living & working (workshops) spaces, social-cultural-sport centres, etc.), their locations in rock masses and the surface land parcels coincided with their ground surface coordinate locations. They should be regulated for land ownership purposes, (for both surface structures and underground spaces). In order to understand the concept and coverage of the underground and surface structures, (with their interrelated impacts), land ownerships with adjoining responsibilities must be defined in legislative manners. Because when the stability analyses are in consideration man-made structures on the surface or underground have their impacts among them which should be regulated according to rock mechanics concepts. At this point, the study performed by Ulusay, etal., (2013), could be mentioned to present the stability analysis for an underground congress hall as an example.

In computer applications, developments in computers and graphical modelling software have gradually improved in 3D modelling of the required earth locations. For example, Huang, (2022), mentioned Pan, etal., (2018), who wrote about GIS, (Geographical Information Systems), a database for Singapore including information from 60K boreholes. Similarly, Huang, (2022), mentioned also about the study of Price, etal., (2018); including GIS applications and the development studies of "3D engineering geological ground model beneath the Earls Court development area using subsurface 1D, 2D and 3D geological and geotechnical data and information". Actually, 3D graphical models have tried to be developed through computer technologies for "official data documentation & protection" purposes. Thus, these efforts are some of the reasons why some countries start research on 3D spatial volume identifications with their 3D coordinates.

Defining 3D land ownerships and governing of the 3D land registrations are not just limited with the official documentations of 3D land parcels. Countries that have their 2D land parcels registration have already applied for ground surface areas. Registering underground volumes for underground spaces, (including museums), have their dependency on the stability of the other underground and surface structures around, (Gokay, 2023b). If rock engineering concepts are not considered here, 3D land ownership will turn into legal dilemmas, (Gokay, 2023a). There is another graphical modelling opportunity which has been gradually used worldwide, and it is named as BIM, (Building Information Modelling). This computerised model has been introduced specially for civil engineering purposes to keep construction related information in standard digital data file form. There are also attempts to gather 3D earth crust location related information including geological information with surface & underground structures' position. One of these studies, (Fig. 2), is a joint project study of the Swiss Cadastral Survey and the Univ. of Applied Sciences of Geneva as Huang, (2022), reported. The discussions concerning the ownerships related to ground surface land parcels and underground spaces have introduced new understanding to governing of land ownerships.

For instance, Jalil&Arshad, (2020), wrote that underground spaces are used for many purposes apart from their convenient advantages in transportation systems. They are suitable also for different civil opportunities like; recreational areas, storage & shelter spaces, service-utility purposes, etc. Within these development trends in the world, underground spaces have their adjoined questions to be developed in urban areas without impacting negative influences to other surface & underground structure rights. Organising underground museums facilities which extend under the surface lands which have several surface land parcels owned their rights with different people, need to have legislative Act to be started. Because any structure excavated & constructed on land surface or underground influences its neighbourhood. They are open

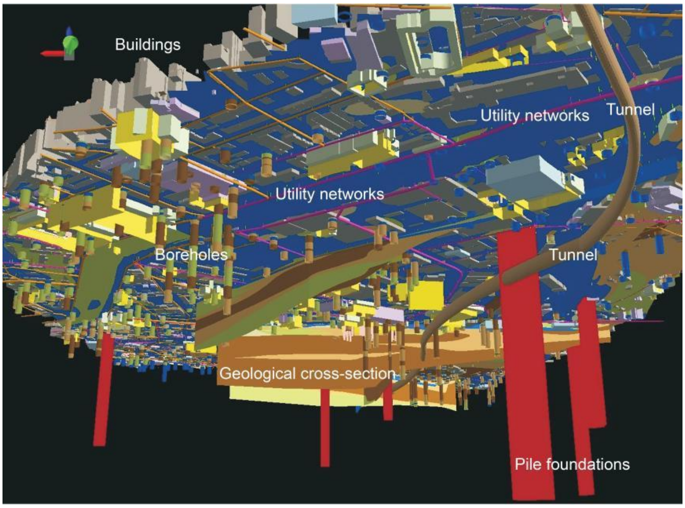


Figure 2. 3D models of cities generally cover illustrations of 3D buildings and surface structures over the cities' main zero datum. Through the joint project handled by the Swiss Cadastral Survey and the Univ. of Applied Sciences of Geneva, 3D model of Genova city realised by combining BIM related data and geological data to illustrate underground extensions of surface structures together with UUS including museums if there are any, (Modified by Huang, 2022, from Baumberger, etal., 2019).

to get stability influences from their nearside surface & underground structures as well. Thus, the attempt in some countries to define underground spaces in different underground parcel ownership rights, (which are not adjoined to any of the ground surface land parcels), have opened deep discussions. Actually, when the usage of land parcels is gradually differentiating from horizontal to vertical, (increasing the number of high-rise apartments and surface structures which have several basement levels, underground storage units and metro tunnels & stations are current developments in cities which are the example of the vertical land usage opportunities), there is a requirement in legal framework to regulate their rights in land ownership procedures. Zhang, etal., (2020), noted the followings in the land ownership subject; "*The booming of three-dimensional, (3D), land use brings a change of the connotation of land rights, which will expand "flat" 2D land legislation 3D land legislation"*. They also pointed out that the legal framework is *"crucial"* for underground spaces. They analysed the *"173 representative laws and regulation"* supplied for UUS in China between 1998 and 2018. They forwarded that *"poor legal framework of urban underground space"* together with adjoining parameters cause ownership disputes. These types of chaotic conditions in underground registrations and their ownership rights including responsibilities force the governments to regulate them in an ordered manner. The owner of the surface land has the right to construct surface structures on the land according to master urban plans. These plans should be provided by considering these structures foundation stabilities, the stability influences of their foundations on the neighbouring surface structures, lighting from sun, airflow passage rights etc. are all must be set to offer construction permissions for planned urbanisations. After introducing the underground spaces, stability & safety of the structures on the surface and underground should then be considered carefully accordingly.

There are also other considerations engineers must think about while attempting to build surface or underground constructions. The surface lands are naturally supporting stability of their own and neighbours. If you excavate a deep foundation area for a surface construction, neighbouring lands' horizontal supports are partially or totally eliminated. In some cases, neighbouring land parcels slide down to the newly excavated areas. In the events where the neighbouring horizontal land supports are withdrawn and causing slides, "the owner of the land is entitled to recover". Sometimes these sliding lands have surface construction on them which might be damaged, (there is possibility to have disastrous fatal accident events). Horizontal & vertical land supporting rights of surface lands should then be maintained while constructing new structures near them. Maidin, etal., (2008), wrote that "*the right of support is negative in its nature. It does not accord landowner a right of support from the adjoining property. The negative right merely gives right to the landowner if the existing support from the adjoining property has been interfered with or lost".* While the stability cases for surface structures are complex enough, providing a plan to excavate a new UUS, or exploring unrecognised underground spaces which are historically important introduces new dilemmas to the surface land ownership rights and responsibilities. Any engineering activity which is influencing, (interfering), the neighbouring surface & underground lands, (structures), ought not to cause any stability problems there. According to Chew, (2017), the extent of "right of support" and compensation to the affected parties must be considered, addressed, properly. These features related to ownership rights influence museums structures at the surface & underground. Any damaging impacts through neighbouring surface &

underground structures, (or any new planned excavation & constructions), on surface & underground museums need to research coincided with rock mechanics contents. Supplying quick decisions for the stabilities of museums include decision-makers' responsibilities.

When there is explored an underground space which is important in historical & archaeological points, there are options to be followed. In the first option, it can be kept as its original situation and do not attempt to open for public attendance. This might be the option to be taken by museum related officers, (engineers, directors, employees), if the underground space locations and positions have severe stability difficulties. In the second scenario, historical underground spaces, (which are going to be explored for further extensions of the spaces before declaration of the underground museum), are underlining crowded city, (or agricultural), lands. In this case, underground space related influences are required to be analysed for surface and underground structures. Any underground space which has not been explored through earlier times, (exploration research), have their own circumstances. If there are no detailed descriptive legislative Acts, about this kind of archaeologically & historically important but forgotten, (or undiscovered), underground spaces, any collapse initiated due to these spaces influences the surrounding rock masses could be problematic. If a partial collapse occurred at such an underground space after its declaration of an underground museum, engineering and legal issues might be asked to deal through the museum authorities. Therefore, it is important to define land-ownership rights and responsibilities for underground spaces besides legislative Acts regulating rights and responsibilities of surface land parcels.

Actually, there are special offices in governing ministries dealing with urbanisation in countries. Furthermore, all the urban parcels planned through master plans, (land-parcels of existing settlements, and land-parcels of the planned recent urban areas), should be analysed for their stability conditions through rock & soil mechanics principles, (including their behaviours for the cases of earthquakes).

Detailed field measurements & research which should fulfill the required preliminary studies to collect design data for the mentioned analyses might also cause to locate undiscovered underground weakness zones, faults and underground spaces under the existing & planned urban settlements. If the discovered underground spaces are historically & naturally valuable and required protection for their heritage characteristics, underground museum plans may be set for them to organise their secure, stable, and safe exhibitions. These kinds of underground museum spaces cover the stability related legal decision parameters which are evaluated for common UUS. These parameters are explained in UUS literatures but generally include the following main topics; Concepts in surface/underground land ownership rights and responsibilities; Stability of surface / underground structures; Responsibilities defined through legislative Acts; Rights & responsibilities defined for surface & underground museum visitors & employees in cases of accidents. It should not be forgotten also that "extra" underground passageways, tunnels, excavations might be required for alternative exit paths, (to the ground surface), for underground museums. Therefore, excavating these extra passageways after getting special permissions through related ministries which have their duties on national heritage protection needs also stability analysis based on field data and rock & soil mechanics analyses. Thus, underground museums should have their rock mechanics reports before their further explorations studies. The results of these analyses put forward if the existing underground spaces required support to protect them from rock failures causing partial collapsing of them.

International tunnelling association policy statement on subsurface planning was presented in ITA-Report, (1991). The pre-description words before the statements pointed out that; *"The Working Group on Subsurface Planning of the International Tunnelling Association has adopted the following general policy statement on the needs and benefits for planning of subsurface uses*". The statements include; "*The subsurface is a resource for future development similar to surface land or recoverable minerals. Once an underground opening is created, the subsurface can never be restored to its original condition and the presence of this opening can affect all future uses of the surface and the subsurface in its vicinity. These factors require responsible planning for all uses of the underground to ensure that the resource is not damaged or usurped by uncoordinated first uses. The awareness of the underground option among planners, developers, and financiers should be increased so that subsurface planning issues are properly addressed. Subsurface planning should be an integral part of the normal land use planning process".*

At this point the work performed by Al-Shanty, (2019), is required to be mentioned here, the author summarized the earlier underground cities and explained the futuristic plans for new houses in urban locations which could possibly be located underground in future. Actually, different design options in different countries have demonstrated that underground civil purpose spaces are currently convenient options for extreme, (hot and very cold locations in the world), weather conditions. Papers and booklets have been pressed for their presentation to form public awareness and their safety precautions like in; Vähäaho, (2014a, 2014b, and 2021); Wikipedia, (2022); Seng, (2022). Underground space development for different usages is exemplified by Kwet-Yew, (2018), for liveable city environments. Architectural designs alternatives bring new understanding for living & working volumes at surface and underground settlements. Underground museum opportunities should also be considered for heritage & natural asset protections in these kinds of regional master plans. Engineering evaluations of museums for the explored historical underground spaces have required extra considerations to match the high number of visitors handling and their safety precautions. Think about an official underground mine visit by government officers or research members, they have to be informed about the applied safety rules through compulsory briefing meetings and they have to accept the applied rules to obey. In addition, they are already informed about the danger of collapsing the galleries due to uncertain parameters, (natural characteristics), which had been pre-assumed during mine, (or underground excavation), designs. They also have to carry required safety masks, electronic location sensors to position their location in the mine through remote monitoring system, and any additional items for their personal safety. The question should be asked here if the entrance perquisites of underground museums for each person, (including visitors, employees, etc.), who would like to enter the underground museums should be similar? If they are permitted to enter underground museums like surface ones, what could be the additional design factors engineers and other professionals must evaluate for security, stability and safety of the underground museums? These are the essential questions which their answers should be listed in the related underground museum legislative Acts and rules clearly.

Underground spaces have certain similar considerations when the safety issues are started to be evaluated. Firstly, since they are underground volumes, there is outside access in case of fire, floods, explosions, etc. The access can be supplied through underground main entrances, ventilation shafts, and emergency shafts & galleries opened earlier for rescue operations. Secondly, visitors and employees in the underground museum halls do not have quick access to ground surface. They have to be directed for safe emergency access to outside in the case of accidents. Thirdly, the time passing after certain accident types is very important for underground museums, because underground spaces have tendency to be encapsulated and impacted with flood waters, smokes of fires, shocks of explosions, very hot and fast by-product gasses distribution along the underground spaces, etc. Therefore, all the accident related precautions, rules and rescue operations should be considered & prepared by evaluating physico-chemical characteristics of material used in the underground constructions, and rock engineering concepts to validate underground space stabilities in the cases of accidents.

Since; underground mine operations are continued by excavating required mineral or energy raw materials through applied mining methods. These methods usually leave open, backfilled, or purposely collapsed gob, (underground), volumes at the mined out sections of the orebodies. Underground museum operations facilitate only at the open&stable underground spaces which had been excavated earlier times, (as mine stopes |& galleries, or man-made shelters, depots, etc.), these spaces can be parts of natural cave-network as well. When it is decided that certain underground spaces have their value in nations' cultural-social-industrial-historical-archaeological background, it should be protected for next generations. When certain underground spaces are going to be declared as the underground museums, there should be special designs for alternative, (separate), passageways, exit-tunnels to ground surface for their emergency accesses. Underground spaces, halls, saloons, theatres, extra emergency access passages, etc. related to the underground museums, then have to be evaluated altogether and different plans should be provided by complete/combined considerations. Since underground museums are organised for public access, their security, stability and safety cases should also be defined like in the case of legislative Acts supplied for underground mining operations or main road tunnels. Bettelini, (2020), for instance wrote about the safety cases of road tunnels. Due to accidents and loss of lives at road tunnel accidents, the safety rules provided by European countries for these tunnels are strict for the drivers and tunnel operators. The other underground spaces actively used in different countries for urban activities have to be regulated also to obtain efficient benefits out of them. Jalil & Arshad, (2020), wrote that "*there has been no comprehensive analysis on legal aspects concerning with the underground developments as law always play a silent partner in property development. In the absence of supporting legal framework, the full potential of underground development may be hindered, slowed and abandoned*". Therefore, officials of underground museums should be ready to answer the questions related to museums' stability analyses and monitoring steps starting from pre-planning phases of the underground museums. All the accident types must then be pre-evaluated for the targeted underground museum operations. Evaluations and analysis followed in this concern must also be filed and reported officially to governing bodies with their sealed double copies, (kept in two different locations & systems).

3. Accident protection parameters for surface & underground museum structures

In general, visitors & employees of the museums have the feeling that they are in stable and safe surface/underground structures. The following questions should be asked here to have deeper evaluations; How the safety of the visitors have been supplied? and Who is responsible if any fatal accident happens? In countries, the legislative Acts could be different for surface and underground structures.

If the surface museum is a new construction structure, they have been planned & designed with specially purposed artistic features. They usually have architecturally attractive buildings. Due to the special requirements of the volumetric “protected spaces” for different exhibitions, museums have their different galleries, saloons, halls, etc. according to their archaeological, historic, cultural, etc. items. Thus; “Natural history museums” and “Art museums” have their specially designed surface structures in modern cities. Besides them, there are also historical surface structures such as; houses, castles, bridges, etc. which are dedicated to be protected as themselves. These surface structures have been kept as possible as their original conditions, (situation). According to their stability and safety concerns, visitors have been asked to either walk in them properly, (rule applied), or they are asked to follow specially constructed walking platforms to protect visitors' safeties and historical structures' stabilities. There are many decision parameters influencing museums' structure intactness in these concerns, but vibration formed due to visitors' movements is one of the factors which should be analysed for the protections of the museums' stabilities. In order to prevent any case of structural failures based on historical museum structural instabilities, civil and ground engineering analysis should be followed. Periods of structural controls by engineers and related professionals should be organised and their reports must be filed at least two separate manners orderly. Since these kinds of surface structures may need extra reinforcements, these should be planned through professional groups of engineers and contractors by handling special permissions for each step of their actions about these surface museum buildings.

If a defined "historical museum" is an underground mine, cave, shelters, depots, or an underground city, what are the precautions defined for visitors & employees in the cases of collapses, roof failures of underground spaces, rock bursts, floods, fires, smokes, discharges of natural gasses, etc.? Ministries handling museums in every country have their safety reports for each of their museums together with their risk assessments of accidents through the professionals. Fire departments in modern municipalities have their reports for each surface building for their operations in any cases of fires. Engineers and directors of surface and underground museums should be aware of their responsibilities, concerning, if there is a requirement of periodic stability checks for the museums structures. In any case, they should perform their periodic security, stability and safety controls and documents for the museums they worked for.

Common accident types expected at museums can be listed below to supply required precautions and duties to follow by museum officers. The problematic cases are: a) Partial collapsing occurred at "surface museum buildings" or "underground museum spaces", b) Fire outbreaks, c) Explosion due to museums' facilities & instruments, d) Explosion due to terrorist attack, e) Water inrush due to "surface building pipe failures", "roof failures at the surface museum structures during heavy rains", f) Flooding due to flush discharge of groundwater into the museums' spaces, g) discharge of rainwater through underground fractures into museums' halls, h) Flooding due to heavy rains, (or melting of the snows), i) Smoke dangers originated due to open fire or any type of machine related operations, (smokes can be poisonous as well), j) Uncontrolled movements of the visitors in rush, k) Vibration due to blast or machine operation which is higher than permitted limits. These factors are then analysed individually to supply related precautions to prevent accidents occurring at the museum structures.

4. Parameters influence visitors' safety at underground museum conditions

Surface structures have several options for rescue operations if their height are limited. High rise apartments on the other hand have their own risks in case of fire and earthquake incidences. Underground structures, one of them is underground museum structure, also have limitations in emergency rescue operations. Thus, when the subject is underground spaces and their accident related rescue operations, then experiences gained through underground mines are valuable assets for underground museum related rescue team activities. Similar facts could be expected for UUS facilities including underground museums. Monitoring weather conditions for heavy rain incidences, (for example), might help engineers to be prepared for further catastrophic facts. These kinds of heavy rain occurrences are usually the main reason for flooding of the wide land areas, regions, which might include underground museum structure as well. In similar consideration, Niira, etal., (2016), presented facts about the flooding of underground metro stations after heavy rain in Tokai, (Japan), in 2000. Underground cities, shelters or museums might have similar features in this concept, if the volumes they are providing are the lowest level for rainwater to be accumulated. However, there are other possibilities according to the positions of underground museums. Such as; if they are located at rock masses which have several conduits to get the groundwater or surface water bodies, (such as; flooding originated flush water), from the main, (high elevation), ground surface, and these rock masses have also conduit networks to discharge their water contents into deep valleys, underground spaces in these kind of rock masses could be less influenced from flooding. Effectiveness of these conduits totally depends on the amount of charging water and these conduits' water discharging capacities. Additionally, solids transported through flooding waters are also very effective in this kind of rock conduit charging & discharging capacities, they may most probably form obstacles for these conduits and change their water charging and discharging capacities.

Donsimoni, etal., (2008), presented a karstic model which has charging and discharging voids. If there is no discharging conduit for underground museum spaces, water, (groundwater or flooding), inrush into these spaces fill the available underground volumes unless there is a high capacity pumping system to discharge these water bodies. Jouves, etal., (2017), for example, worked about 3D conduit networks which supply drains for groundwater flow at karstic rock mass. They worked on 26 caves to collect data through karstic patterns. They wrote that their study “shows how important it is to relate the geometry and connectivity of cave networks to recharge and flow processes”. Urban master plans have examples of wide and almost flat regions with small irregularities in elevations. These locations are dangerous areas for the cases of flush heavy rains, especially if the surface water discharging rate is getting lower with respect to rain water charging due to its low elevation differences, rain water accumulation on surface and their danger to directed into underground conduits or man-made underground spaces, (metro lines, stations, carparks, culture-sport-social centres, shelter, museums etc.), have its potential to become disastrous fact for the local people during these kind of conditions. The conditions could be turned into a national disaster if the number of people captured by flood without quick help or rescuing operations. Therefore, entrances of underground spaces like underground museums should be specially constructed to avoid heavy rain waters and flooding impacts by supplying a certain degree of protection.

Experiences gained in underground mining operations can be used for urban underground spaces as well. In order to provide disaster precautions for underground museums, the danger of flooding should be evaluated and supplying extra underground volumes as “underground water collection galleries” could be one of the solutions to avoid negative impacts of flooding. Excavating these galleries at a lower level with respect to the available underground museum levels can be the solution. Planning them with large volumetric capacities together with large capacity pumping units may supply flooding protection for underground museums. Monitoring the stabilities of these flood water collection galleries and "ready to operate water pumping system" are engineered carefully to discharge the water to supply a safe museum environment for visitors, museum employees, and artefact, (exhibited in the underground museums).

Li, etal. (2024), wrote about the danger of the flooding of underground facilities in China while increasing the number of general floods events in the last ten years. They reported that the average number of floods is around 154 per year for China. Flooding in urban areas has caused economic loss and fatalities. These authors pointed out that the flooding disaster at Zhengshou, (China), in 2021 influenced underground spaces as well and 39 people drowned at metro tunnels and basements. They also wrote that "Once external water invades, it can quickly spread to the entire tunnel space and the water level will rise extremely fast". That means discharging of the flood-water cannot be managed in a short period of time. Therefore, engineers should think about other available options besides quick response of high capacity water pumping of flood-water through several locations. Engineers might design high capacity water discharge passageways if there are ground surface locations where their altitudes are lower than the underground tunnels, museums. Think about an underground museum for natural heritages of karstic features at the level of unsaturated conduit presented in Fig. 3. At this location there is a possibility of discharging flood water into surface waters through available karstic water passageways. Engineers might prefer to excavate extra tunnels for water discharges to the river in case of flooding events happening with extra amounts of water and muds. For the case of underground spaces where there is no option to discharge the water through tunnels to the ground surface. Engineers have their obligation to put obstructs to delay or direct the flush surface water charging into other purposely excavated underground spaces. Li, etal., (2024), mentioned early-warning evacuation and they added “sub-regional anti-flooding doors to control the flow of water are powerful measures to reduce the disaster loses”. It is important to notice that; commuters of underground transportation systems, visitors of museums, employees in urban underground spaces, etc. have known the dangers of underground spaces and they should be informed of the emergency measures and emergency exit route. Engineers on the other hand have their obligations in their design to predict flood events and prepare their underground space projects in a way that it might have separate sectors which have several water-tight doors to keep the flood water in separate underground volumes to gain valuable escape time for the evacuation operations handled to rescue the people from underground.

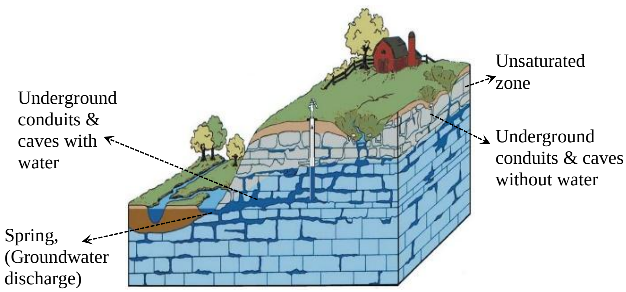


Figure 3. Conceptual model showing “a cross section of a Karst bedrock setting£. In some cases, unsaturated conduit & cave spaces could be accessible by public for their karstic features through a natural heritage museum. (modified after Iowa Geologic Survey; Iowadnr, 2024).

Another life threatening dangerous accident in underground museums is fire danger. If a fire starts due to machine failures or inflammable gas & liquids, burning of facilities causes unrecoverable damages. This is one side of these events. Another side is “poisonous and suffocating smoke effects” which cause fatalities away from the fires hot-points. Thus, underground ventilation systems should be designed for the normal operations and for these kinds of unexpected fire cases as well. If it is possible, urgent high capacity ventilation systems with airflow-doors, (to direct the airflow through underground galleries), should be ready to encapsulate fire outbreak in limited sections of the underground spaces. Fire extinguishers and water sparkling systems must be active at all times to extinguish a started fire while they are on a small scale.

Other human related accident types can be seen at underground space operations like; falling from height, dropping heavy weighed material/instruments, dealing with the machines which have moving parts without paying attention. Inadequate monitoring jobs, and misaimed analysis performed for underground space stabilities are also be considered in back analyses of any accidents happened at underground spaces. Actually, following observational & testing methodologies, or numerical analyses results for induced stress-strain conditions might cause different results. Engineers should be aware of the real-world conditions of their stability problems by accepting uncertainties in measured rock properties and behaviours. Handling classification methods, numerical analysis, average values, failure criteria, etc, must be evaluated through engineering senses, accuracies and experiences. When the responsibilities are concerned, uncertainties in rock mass related parametric evaluation methods should be mentioned in legislative Acts to point out the importance of the uncertain facts. Thus, why Eurorule7 approaches for ground engineering, (soil and rock), projects try to include these facts with their risk contents. This approach is more realistic and keeps the engineers on the safe side for the cases of accidents. Defining mechanical conditions of rock foundations in civil engineering, or rock behaviours surrounding the underground spaces as “stable” without mentioning details in related risk assessments cause legal dilemmas in case of accidents. In the mining or rock engineering field, all the employees and engineers know that, if there is a statement for underground spaces as “stable”, that does not mean that, it is stable all over its service-life. “Stable underground spaces” statement means that, according to available knowledge, observational records, and collected field-laboratory test data, underground space under considerations “seems most probably stable”. But it might collapse in any time also due to sudden changes in induced stress conditions which naturally includes a high amount of uncertainties.

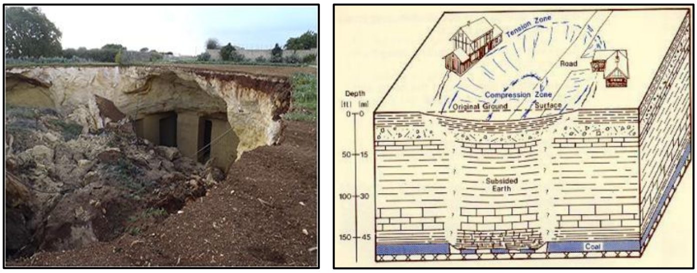
5. Evaluation of responsibilities for underground museum operations

Underground spaces have mainly three phases if they are evaluated for their stabilities, these are planning&designing, excavating&construction, and operation&monitoring phases. Operating historical/archaeological; underground spaces, caves, or abandoned mines as museums for their values have their security, safety, and stability issues as well. Countries might have underground caves, historical underground shelters, or underground cities according to their geological features. Exploring historical underground spaces is one side of the research. After their exploration, they have to be protected from unofficial entrances. They have to be conserved as they are and they should be stable in conditions. If there are unofficial visits by people for these underground spaces, these actions may put their valuable contents into danger, the visitors may damage, (unintentionally or purposely), their integrity, natural features, and historical remnants in these spaces. Additionally, sometimes handling these spaces to organise them as underground museums might cause problems as well. Missing profession in the museum organisation committee who are dealing with the stability of these spaces is an unseen problem that arose in further times. Therefore, countries should better organise special governmental offices for their underground museum operations. Because, after underground museums are open for public services, the operational safety of them and stabilities of the spaces include long-term monitoring jobs overwhelmed by engineers holding their responsibilities.

To demonstrate what can be the responsibilities related to underground museum stabilities, the case supplied by Kaljuste, etal., (2021), could be considered. These authors mentioned the secondary usage, (as an underground museum), of an abandoned underground mine, (Nowold Kohtla mine in Estonia). They wrote that this mine is used *"as an underground museum to present for local people and tourists how mining works were carried out in the past (Estonia has 100-year-old experience in oil shale mining)".* Similarly, some other countries which also have mining histories would like to handle some of the abandoned underground mines as underground museums. Whereas, secondary usages of the certain abandoned underground mines create complex situations in their safety concerns. For example, Ivanov, etal., (2020), wrote that "*using such* *space creates some dualism in its maintenance*". Just before the abandoning protocols of an underground mine, the mine had been operated under mining law of related countries, and health & work-place safety conditions of that mine had been engineered for each shift by responsible mine engineers. After the mentioned protocols, if some of the mine galleries or stopes, (or whole mine), are started to be organised for their secondary usages like; depots, shelters, or as a historical museum, health & work-place safety conditions may not be considered under mining law anymore. Because legal working conditions of these underground galleries & stopes, (underground spaces), should be re-considered under urban underground space conditions, (via related legislative Acts). The concerning abandoned underground mine spaces usages are different in their secondary usages but, the stability of them could be influenced by induced stresses which have been continued to differentiate through the earlier mining activities. Operational safety rules followed at Wieliczka Krakow Saltworks Museum, (Poland), were supplied with enough clues which these kinds of underground museums must follow to secure their visitors' safety (Wieliczka, 2021). Terms and conditions of touring the Wieliczka Salt mine museum includes basically; general conditions, availability of the mine, booking & sales, general touring rules, safety rules, final provisions. Beside these museum operational rules, there should be other stability and safety rules to be followed for underground museum safety. Therefore, safety precautions for any underground museum organisation which facilitates abandoned underground mine spaces should include underground stability monitoring systems. Similar monitoring systems should be necessary for underground museums organised through urban underground spaces other than abandoned underground mines. Stability and safety monitoring systems of the underground museums include induced stress-strain measurements at certain test locations selected along the museums; spaces. Internal dimension measurements of the underground museum spaces are also included for several of the selected positions of the spaces. The data collection should be in continuous circumstances and their analyses are required to be performed through rock mechanics contents with defined responsibilities, (including official reporting of the measured data and analyses results). Any unexpected differentiation in measurements could be the early sign of rock deformations which engineers might provide essential extra support procedures. If the rock failures are detected much larger in scale around the underground museums, the visitors and employees must be evacuated according to set-up evacuation rules.

Accidents and disasters which could be happened at surface and underground museums have their reasoning and they have their pre-defined precautions, (when the common types of accidents are in consideration like; flooding, fire, smoke, fall from height, conjunctions due to panic movements of visitors, explosion due to inflammable gases and liquids, etc.). When the underground museums are in consideration, protection measures prepared against the collapsing of underground museum spaces are aimed to supply safe & stable underground museum spaces for the visitors and museum officials. Similar stability cases must also be considered for surface museum structures, (they also have to be structurally safe & stable to accept visitors).

In order to present engineering works followed to predict the stability of the underground spaces, analysis performed by Rafeh, etal., (2015) can be an example. They concentrated on "*the* *mechanical behaviour of the cavities affected by presence of joints and fractures in the chalk layers*". The cavities mentioned in their paper are rooms of historical, (shallow), room & pillar mining activities. Their stability is the main concern "*in North France and its region constitute a risk of damage on both people and* constructions". Authors performed numerical analyses to understand the effect of joint sets on the mechanical stabilities of these chalk mines. They stated also that discontinuities in the rock masses around abandoned underground mine spaces affect theie stabilities. In their words *"Joint orientation provokes different failure mechanisms in the roof and/or pillar for the same case of geometry of the cavity".* These analyses performed for the safety of people and any constructions just over these cavities. If some of the open spaces in these chalk mines are used for underground museum activities, the safety of the visitors who enter these historical abandoned mines are main engineering concerns. For this circumstances, when the rock engineers think the stability conditions of similar shallow underground stone mines, (which historically or currently have been operated in different countries), each one of these mines have to be analysed for their roof & wall rock stabilities in case of any consideration of underground museum through their remnant spaces and galleries. To illustrate the danger of the sudden roof collapse happening at these types of mines, (Fig. 4), the event happened on Nov. 21, 2014 in a shallow underground calcarenite stone mine, (Fig. 4a), at Marsala, (Italy), is an example. This mine was abandoned in "*the half of last century*". Part of this mine collapsed to form a sinkhole that originated due to man-made mining activities, (Gutierrez, etal., 2014). Similar research works were performed for the historic underground spaces of "*Cave di* *calcarenite in Contrada Cuccidenna"* at Marsala, (Italy), which "has been recognised as a typical example of industrial archaeological heritage", (Zimbardo, etal., 2013). These authors evaluated the abandoned underground spaces' stability conditions through rock mechanics content and numerical analyses. They noted their observations about the underground quarry rooms' excavation procedures for their stability cases. They also added that "*plasticization of some areas occurs as a consequence of excavation and safety condition get worse*". According to them, degradation of surrounding rock masses around the quarry rooms may cause further instabilities. These conditions need further analyses to be sure about their safety for touristic visits of these historical mine sites. Continuous monitoring of these spaces' stabilities are also required for visitors' safety together with the ground stabilities of the surface structures over the extent of these underground mines. Underground spaces formed in earlier time, through underground quarry activities have similarities according to Parise & Lollino, (2011). They wrote about the rock mass, (the Pliocene–Pleistocene calcarenite), mined in the Apulian area, (Italy). These authors wrote that this rock is "*a typical soft rock*" and it "*was extensively quarried underground, by digging long and complex networks of tunnels*". Like the other historic mining sites, excavations had been continued for years before they were abandoned. In general, there is no historic documentation related to them. When the last person who knows some galleries or rooms,



a) b)

Figure 4. a) Sinkhole formed due to the roof rock collapse of shallow underground calcarenite stone mine at Marsala, (Italy). Thickness of roof layers, (and abandoned mine spaces), can be seen clearly in this photo "taken on Nov. 25th, 2014, only four days after the sinkhole opened", (Photo: Parise, M.), (Gutierrez, etal., 2014). b) Sketch of subsidence effects due to underground flat-seam coal mine opening collapses and related caving, (IllinoisDNR, (2023).

spaces, entrances about them have gone, their locations, depths, extensions, collapsed parts, mining methods, roof supports, etc. are all lost away. In current times, any urban site over these shallow underground mines, have their dangerous conditions of sudden occurrence, possibility, of sinkhole, subsidence influences of earlier collapses, etc. Parise & Lollino, (2011), mentioned similar dangers for Apulian towns, (Italy). They supplied their numerical analyses outputs to illustrate induced stress concentration differences around the underground mine spaces. Any museum activities which could be organised for these underground quarries might have a similar collapse case if the rock mass around the underground museums are left unintentional, (without stability monitoring). Pellicani, etal., (2017), also reported historical shallow underground stone mine effects on the ground surface at Altamura, (Italy). They visited the accessible spaces of mines to exemplify the rock failure types. Their analyses about the stability conditions of the surface locations above the mine spaces are valuable assets for local people. They presented a susceptibility map for instability for Barcelona street at Altamura, Italy. Positions of mine spaces and stress maps of Altamura were overlapped to illustrate unstable locations.

Similarly, Bulko, etal., (2023), wrote about the underground shelters & tunnels named as “Cachtice underground”, located under Catchtice village in Italy. These 16th century underground spaces had been used as cellars. They were used as shelters during World War II as well. According to authors; after years, some parts of them were repaired to organise historical events. They wrote that “Due to a lawsuit, the Cachtice underground was eventually closed to the public, and it was necessary to test the stability of the walls of the Cachtice underground”. The law suit case which had happened for these underground spaces, is going to be applied for all kinds of underground spaces opened for public usage in time. Similarly, when there are forgotten historic underground spaces, or caves discovered near an urban centre, municipalities would like to turn them into underground museums to raise their tourist attractions. However, without appropriate legislative acts describing all sides of responsibilities, duties and ownership circumstances for these kinds of underground spaces, officials and engineers in related underground museum operations have their full risks in their explorations, developments, and operational activities. If a fatal accident happens due to partial collapses of underground museums’ roof rocks, (or their walls), professionals responsible from the underground museum spaces’ stabilities have to explain their reasoning according to the available legislative Acts supplied for surface and underground museums. If there is no special legislation concerning museums' safety, security and stability in certain countries, they should rather work on these facts to specify the responsibilities of; related ministries, municipalities, museums governors, museums officials, safety controllers, stability monitoring officials & engineers, visitors, etc. purposely in surface & underground museum operations.

Caves as underground spaces are used for living environments in history. Their usages have been continued as far as their practical advantages are continued. Some caves have their special features in terms of stalactites and stalagmites which cause them to be declared natural underground museums. However, like all the other underground spaces, their stabilities should be analysed for the visitors' safety concerns. For example, collapses of caves in Gaziantep, (Turkey), urban limits have formed dangerous situations for the people using these caves for domestic purposes and the people having houses just over them, (Fig. 5b). When the geological map presented by Canakci, (2007), is checked for the number of stable and collapsed caves near Gaziantep, (Fig. 5a), the importance of cave stabilities is realised much more clearly. Roof rock/soil masses collapse cases have been reported for many man-made underground spaces and one of them was at "Chaoyang mountain tunnel", (China), (Fig. 5c, 5d). The length of the tunnel having roof caving problems was reported as 10-20m, (length of the tunnel; 500m). The collapsed roof had "funnel-shaped pit with a depth of 6m and a diameter of 18.3m on the ground", (Li, etal., 2020). There are several other collapse cases for man-made underground spaces, (like; tunnels, depots, shelters, machine rooms, urban underground spaces, etc.), which have been reported through related research.

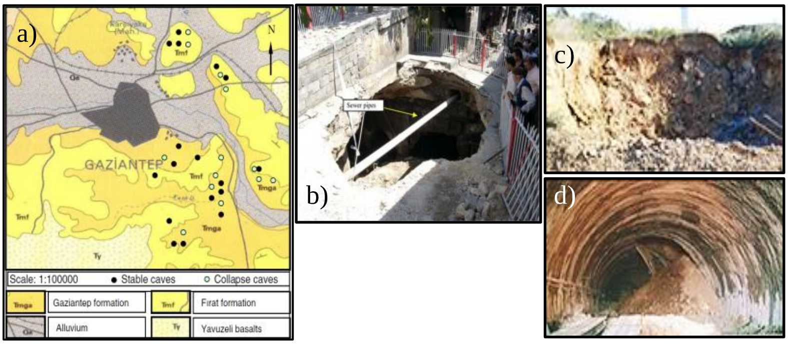


Figure 5. a) Scaled map of Gaziantep, (Turkey), showing stable and collapsed cave locations together with the basic rock mass types and rock formations, (Canakci, 2007), b) Collapsed cave situation at H.Kutlar street in Gaziantep, (Canakci, 2007), c) Caving material observed in the shallow depth Chaoyang mountain tunnel, (China), (Li, etal., 2020), d) Subsidence, sinkhole, observed at the ground surface above the collapse part of Chaoyang mountain tunnel (China), (Li, etal., 2020).

Thus, utilisation of caves & man-made underground spaces as underground museums for instance, could only be possible after their stabilities are analysed and reported according to rock mechanics context. Actually, most of the underground museums have been organised by using historically & archaeologically important underground spaces like; caves, abandoned mines, shelters, tunnels, etc. They are underground spaces formed through different circumstances. Since the types of underground spaces are various, the classification systems supplied by "*the Commission of Artificial Cavities of the Italian Speleological Society*" should be mentioned here. As Galeazzi, (2013), wrote this classification is organised "*like a tree, based on seven main types, in turn divided into sub-types*". The main types of these underground spaces and their subdivisions are as follows; a) Hydraulic underground works, b) Civilian dwellings, c) Religious cult, d) Military & war works, e) Mining works, f) Transit underground works, g) Other works (Galeazzi, 2013). Countries mostly have their traditions and social cultures to organise museums. All these underground space types then have their options to be organised as underground museums to keep the countries' cultural-historical-archaeological, etc. backgrounds alive in societies. However, in order to avoid failures at underground spaces of museums, they should be analysed and monitored for their stabilities. For instance; Kumsar&Aydan, (2021), worked for the stability cases of Kaklik cave, (Denizli, Turkey), through rock mechanics studies including numerical, (discrete finite element), analysis. They wrote that the cave showed itself when part of its roof collapsed due to agricultural land ploughing activities. According to them, "*since then, it is arranged for tourist visits and its stability assessment is of great importance for visitors*". Therefore, it is vital to point out that museum officials, employees, and visitors should get an introductory briefing for possible accidents and related emergency precautions before they step into the surface & underground museums.

6. Safety of underground museums

Professionals especially mining engineers who have education on rock mechanics and experiences on underground spaces are aware of the rock mass discontinuities and fractures induced during rock excavations especially for the rock blasting cases. Dynamic rock loading and related continuous differentiations in induced stresses-strains situations in rock masses have influenced all underground spaces. Therefore, underground spaces are stable as long as the surrounding rock masses have kept their abilities to distribute overburden loads to their side rock masses. Micro-scale displacements have been expected at the roof and side walls of the underground spaces, these displacements could be accepted if they are stayed in elastic limits and do not influence rock masses intactness and behaviours. If these elastic strains cause to form new micro-fractures or if their effects force the existing micro-fractures to propagate in the rock masses, rock masses surrounding the underground spaces are getting deteriorated in long time scales. This might cause collapses at underground spaces if underground rock supports are not applied. Mine engineers have already known very well that, after announcing underground museum establishment for historically valuable abandoned mines, caves, shelters, etc. the effects of the induced stresses-strains differentiation in the surrounding rock masses of these underground spaces, (which have been continued since these spaces were formed/excavated), are not stopped. They are always effective and have the potential to form instabilities. Therefore, developing a new underground museum facility by excavating new galleries, tunnels, stopes, etc., (or facilitating the existing underground spaces), have required rock engineering design efforts. In addition, rock mechanics considerations should be continued during operation periods of these museums by monitoring all the underground spaces against the danger of instabilities.

Shekov, etal., (2019), pointed to the similar dangers for the cases of abandoned underground & surface, (open-pit), mines and caves, when they are started to be organised for mining&industrial heritage museums. They focused on the safety of the museums' visitors and pointed out that "underground space for tourism purposes is often used by the specialist who are unfamiliar with the issues of underground workings stability, that is the reason why tourists are exposed for many hazards”. In order to present earlier engineering activities for underground spaces, safety cases taken into considerations by Frost, (1985), for Louisville Crushed Stone Company's underground quarry operation, (Kentucky, US), were evaluated. He noted that his article includes, Lousville, Building Officials and Code Administrators, (BOCA), related “Basic Building Code” consideration for this underground quarry. As it is logical to expect that, he pointed out the following three main obstructions for the cases of fire protection of these underground spaces. a) Absence of “immediate or direct” access to the exits, (adits & shafts, etc. to the ground surface), b) Exterior access cannot be supplied for firefighting purposes, c) “The inability to readily vent smoke to the outside”. He also mentioned the firefighting requirements of the high-rise apartment which caused to extend BOCA rules with their special code requirements. He wrote that “based on many years of experience with high-rise buildings, a separate building code section, (Section 629.0, "High Rise Buildings"'), has been built into the BOCA Code”. Like high-rise apartment cases, he pointed to the requirements of new code development for firefighter calls during underground space fire occasions.

It is important to note here that accident protections related to underground spaces should be started at these spaces’ design stages. Problems which could be encountered during the excavation and operation periods of the underground spaces include; instabilities, floods, fires, smokes, explosions, blast, chemical contaminations, natural poisonous & explosive gasses exhaust into the spaces, social unrest, terrorist attacks, etc. Rescue operations and related teams need a special access route to these underground spaces which could be used as emergency exits as well. Their plans and all the rescue operations include mainly accident prevention precautions. In this concept, each possible accident-case should be analysed to forward its prevention rules. Since the underground space usage has been getting popular due to economic requirements, their regulations include all the aspects of the accident prevention context. Their controls and responsibilities must also be regulated in legislative manners.

Complexity of underground space usage is focused by Amberg, (2009), as well, he presented that; “underground infrastructures are complex environments, in which (usually because of the great number of users) the risk of tragedy is ever present”. He presented that; “The owner/operator of an infrastructure is responsible for safe operation in normal, maintenance and emergency conditions”. Details of the required works which should be followed were explained by him as; Awareness of the responsibilities; Analyse & recognise hazards and risks; Plans required to approach all the features of responsibilities; National and international legislation Acts should be checked to organise safety measures for the underground spaces “during the entire life time of the facility”; Cost-benefit and residual risks should be considered as well.

When the museums and their dangerous conditions are searched in the literature, common precautions defined for surface museum safety & security rules are listed. Most of the precautions are arranged against the danger of possible fire and flood events. For the cases of underground museums, which are mostly secondary usages of historical or ancient underground cities, shelters, caves, or abandoned mines, they should have detailed safety and rescue plans. For the case of museums, besides the rescue of visitors, employees, etc. the valuable artefact must also be considered together with their planned rescue operations. The visitors might wonder while they are visiting surface & underground museum spaces, if the part of the spaces they are visiting collapsed how they are going to be rescued? In addition, all visitors entering these museum spaces should be informed about the dangers and they should be directed how they should behave in case of collapse/emergency cases. In addition, operators, organisations, directors, etc., (private or state offices), of the museums must have their plan for their underground spaces to be accessible through alternative emergency rescue tunnels, routes, which should be kept stable only for these kinds of operations.

If the road tunnels in operations are considered, there are rules to be followed for their safety, these are summarized by Costa&Domingues, (2019), for the considerations of the tunnels in Portuguese. These rules may supply hints/considerations for the safety precautions of the other UUS cases including underground museums. When the commuters of the tunnels and visitors of the museums are under thought, there are huge differences due to vehicles passages through tunnels which comprise different dangerous conditions with respect to the underground museum's conditions. But, safety issues under contemplation hint for the cases of accidents at the underground spaces. The authors wrote that "The Directive 2004/54/EC on minimum safety requirements for tunnels in the Trans-European Road Network (TERN) applies to all tunnels longer than 500 m, whether they are in operation, under construction or at the design stage". They wrote also that "The Directive has been transposed into national law by The Decree Law (DL) 75/2006, (which has been updated since then)”. Safety of the tunnel-related people involved in construction and operation phases have been regulated through these steps in Portugal. Similar to TERN’s safety rules for tunnels covering additional precautions specifically applied for UUS according to their purposes and gaining methods, (new excavation, enlargement of available UUS, abandoned mine galleries-stopes, caves etc.) should be followed for underground spaces including underground museums. Costa&Domingues, (2019), stated also that, The Decree Law 75-2006 in Portugal defined “structure and responsibility chain” for tunnels; a) administrative authorities, b) tunnel manager, c) safety officer, and d) inspection entity. This Act “lay down technical and organizational requirements covering the design, construction, entry into service/operation and refurbishment of road tunnels”. In a similar subject, Ernst, etal., (2006), evaluated underground tunnels in Europe for their operation and safety considerations. For the cases of tunnel accidents, design engineers should think about their reasoning to have more creative UUS plans and design procedures in the cases of accident prevention circumstances. Ernst, etal., (2006), stated that 713 people had been killed in tunnel accidents between 1995-2006. A few of these tunnel incidents were remarkable historic events. For instance; “39 people died in the fire in the Mont Blanc Tunnel between France and Italy in March 1999, 12 people died in the fire in the Tauern Tunnel in Austria in May 1999, and 11 people died in the fire in the Gotthard Tunnel in Switzerland in Oct. 2001”. When the introductory statement given by Dovey, B. (Chairman, ICMS) is taken into account, (ICOM, 2024), the focus of the museums’ safety defined through the International Council of Museums, ICOM, becomes more clear. He stated that “It is fortunate that disasters do not occur every day in museums and galleries. The very rarity of them can lead to a situation where we hope for the best and are reluctant to prepare for the worst!". Emergency situations and all the influencing factors including museum officials & rescue teams affecting the safety of the museums were explained through ICOM publications (ICOM, 2018; ICOM, 2024). The main content covered; Risk analysis, vandalism, theft, fire, floods, chemical spills, earthquake, terrorism, threat of bombs-rocket attacks & war, and building facility risks.

Corbee, (2016), wrote also about problematic conditions during evacuation of underground spaces in case of any dangerous events influencing the underground facilities. He wrote that "ventilation, limited number of access and egress points, lighting and the effect on human behaviour are some of the problems that can arise in underground emergency situations". He added that combination of these factors with "potential fire hazards makes it important to analyse the evacuation process as emergencies can result in loss of human lives". He analysed the factors influencing the dangerous accidental conditions for underground spaces through computer programs. The exit passages toward the ground surfaces to evacuate people working, (or visiting), underground are considered for their effectiveness. He also mentioned the requirement of rescue chambers at different underground locations to be used by people who could have the possibility of being trapped without any evacuation exits. A thesis performed by Corbee, (2016), presented the study considered for "The European Organization for Nuclear Research", CERN, underground facilities. It was about "the usage of rescue chambers as an alternative to additional egress paths". This thesis report included facts which should be considered deeply before deciding any underground space facilitations for urban activities, (like museums, UUS etc.). Thus, countries having underground museums have their responsibilities to follow similar or much more complex analyses to understand the requirements of exit, (emergency), passages and rescue chambers for different types of accidents. When the safety of the visitors is under consideration, underground space behaviours during any possible earthquake should also be analysed for the cases of underground museums. The time required to see the artefacts and historic remnants at museums' exhibitions usually takes quite a long time. For the cases of situations in which underground museums are influenced by the quakes, the safety of the museums' visitors, employees and museum artefacts should be pre-analysed and the rescue plans must be evaluated. As the usage of the underground spaces are getting increased, they are excavated gradually in deeper locations in the earth crust to avoid their interrelated induced stress-strain influences. In order to visualise the issue, the information supplied by the City and Regional Development Bureau of Japan, (CRDB, 2006a) can be checked for the depths of Tokyo, (Japan), metro tunnels excavated in time scale, (the depth of metro tunnels was "getting deeper from 1959 to 2000). This condition could be the case for different countries as far as the rock masses provide suitable conditions for the planned UUS. The depth of UUS including underground metro lines and museums have influenced the stability of the surrounding rock masses. The depth of underground spaces also influences the behaviour of these spaces in the cases of earthquakes. CRDB, (2006b), revealed that measured tremors in the underground spaces, "tend to get smaller" as the depth of the spaces are increased. Thus, "tremors in the Deep Underground are thought to be much weaker than at the surface of the earth". The work reported by Aydan, etal., (2010), stated also that “underground structures are well known to be earthquake resistant”. However, they also pointed out that underground spaces are vulnerable to seismic damage. They performed model studies to understand the damages at “tunnels, caverns, natural caves and abandoned mines during major earthquakes”. According to their models, despite underground space resistant against shaking, discontinuities in rock masses around the underground spaces influence them negatively and “makes them vulnerable to collapses”.

7. Conclusions

Underground museums have their individual stability and safety conditions which should be engineered one by one by groups of professionals and engineers. In case of emergency conditions, the life dangers of visitors and employees must be pre-determined through several scenarios to provide precautions and alternative rescue plans. Any other operational works for museums which eventually cause a lack of responsibility among the museum related ministry offices, municipalities, engineers, museum employees and museum visitors, might form dilemma turmoil in cases of accidents. Authorities organising touristic assets of countries would like to handle all possible reserve sites, (surface and underground), as museums. However, archaeologically convenient issues related to museum organisations for a particular historical site have their special conditions. There are also security, stability and safety conditions for surface and underground museum structures. Especially, declaring an underground museum for a particular underground space, (historical or newly excavated), has its extra stability and safety precautions which should be evaluated through rock engineering context.

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CHAPTER III

Mermer Atıklarının Farklı Amaçlar İçin İnce Boyuta Öğütülmesi: Gezegensel Değirmen Uygulaması

Çimen Gül KULUŞAKLI[1]
Mustafa BİRİNCİ[2]

Giriş

Çok ince boyutlu malzemeler, son yıllarda birçok farklı sektörde artan bir talep görmektedir. Bu artan talebin sektörel bazda en temel nedenleri özetle şunlardır:

Nanoteknolojideki gelişmeler: Nanoteknoloji, maddenin atomik ve moleküler düzeyde kontrol edilmesi anlamına gelmektedir ve 1 ile 100 nm(nanometre) arasında değişen boyutlarda yapılan bilim, mühendislik ve teknoloji çalışmalarını kapsamaktadır. Mikronize malzemeler, nanoteknolojik uygulamalar için temel bir

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hammaddedir. Süper ince boyutları ve yüksek yüzey alanları sayesinde, katalizörler, sensörler ve elektronik cihazlar gibi çeşitli nanoteknolojik ürünlerde kullanılmaktadırlar.

İlaç ve kozmetik sektöründeki büyüme: İlaç ve kozmetik sektörlerinde, ürünlerin etkinliği, emilimi ve stabilitesi gibi birçok faktörü etkileyen önemli bir bileşen olan mikronize malzemelerin talebi her geçen gün artmaktadır. Ayrıca, daha etkili ve güvenli ürünler geliştirmek için mikronize malzemelere yönelinmektedir.

Gıda sektörünün gelişmesi: Gıda sektörü, işlenmiş gıdalarda ve içeceklerde daha iyi tat, doku ve stabilite sağlamak için mikronize malzemelere yönelmektedir. Mikronize edilmiş baharatlar ve tatlandırıcılar, daha yoğun bir lezzet verirken, mikronize edilmiş emülsifiye ediciler ve stabilizatörler, ürünlerin raf ömrünü uzatmaktadır.

Boya ve kaplama sektörünün gelişmesi: Boya ve kaplama sektöründe mikronize malzemeler, çeşitli işlevleri yerine getirmek için kullanılan önemli bir hammaddedir. Bu malzemeler, pigmentlerin dispersiyonu, akışkanlığı, rengini ve diğer özelliklerini geliştirmeye yardımcı olmaktadır. Ayrıca, daha dayanıklı ve estetik açıdan hoş ürünler geliştirmek için boya ve kaplama sektörü mikronize malzemelere yönelmektedir. Bu sektörler için mikronize malzemelere olan talebin önümüzdeki yıllarda da artmaya devam etmesi beklenmektedir. Bu artan talebi karşılamak için mikronize öğütme teknolojisi de sürekli olarak geliştirilmektedir. Daha verimli ve daha az enerji yoğun mikronizasyon yöntemleri geliştirildikçe mikronize malzemelerin kullanım alanı da genişleyeceği öngörülmektedir.

Diğer taraftan plastik, kâğıt, boya, ilaç, pigment ve gıda gibi birçok farklı sektör için de ince, çok ince ve süper ince boyutlu malzemelere olan talep gün geçtikçe artmaktadır. Bu boyutlardaki malzemelerin kullanımı, ürünlerin kalitesini, performansını ve verimliliğini artırmaktadır. Bu nedenle, bu malzemelerin üretimine yönelik bilimsel ve teknolojik araştırmalar hızla devam etmektedir. Doğal kalsiyum karbonat ($CaCO_3$), çok yönlü kullanımı, çevre dostu olması, ekonomikliği, kazandırdığı özellikler, bol ve kolay bulunabilirliği nedeniyle bu sektörler için vazgeçilmez hammadde durumundadır. Doğal kalsiyum karbonatın en önemli kaynağı kalsit ($CaCO_3$) mineralidir. Diğer bir doğal kaynağı ise, yüksek $CaCO_3$ içeriğine sahip ve gerçek mermer olarak tanımlanan saf beyaz mermerlerdir (DPT, 2001; MPR, 2002).

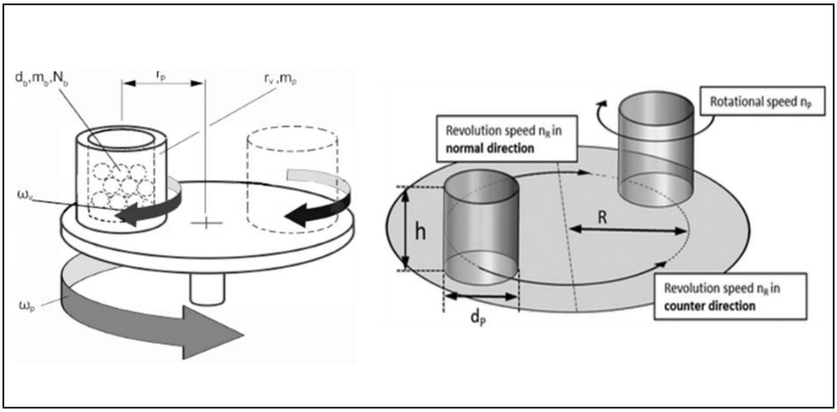
Mermercilik, önemli miktarda atık/artık üreten bir sektördür. Üretim sürecine giren mermerin yaklaşık %30'u net ürüne dönüşürken, %70'lik kısmın atık haline geldiği bildirilmektedir (Onargan, 2007). Diğer bir kaynağa göre ise atık miktarı %75'e kadar çıkabilmektedir (Sağlam Çitoğlu & Bayraktar, 2018). Mermer atıkları inert atık olarak sınıflandırılmış olsa bile günümüzde bazı ülkelerde zararlı katı atık olarak kabul edilmektedir. Bu nedenle, mermer atıkları uygunsuz şekilde bertaraf edildiğinde çevre ve insan sağlığı için potansiyel tehlike kaynağı oluşturmaktadır. Üstelik, bazı ülkelerde mermer atıklarının tamamına yakını uygun olmayan arazi koşullarında düzensiz bir şekilde depolanmaktadır. Bu durumun orta ve uzun vadede, mermer şirketleri için çok daha ciddi bir çevre sorunu yaratacağı ve yüksek bertaraf maliyetleri getireceği kaçınılmazdır (Braga & ark., 2010; Mulk & ark., 2017). Bununla birlikte, mermer atıkları birçok endüstri kolunda farklı amaçlar için kullanılabilmektedir. Bu kullanım alanlarını: (i) yapı-inşaat sektörü ve (ii) yapı-inşaat sektörü dışındaki diğer alanlarda kullanımı olmak üzere iki gruba ayırmak mümkündür. Mermer atıklarının kullanıldığı tüm sektörler için tane boyutu en önemli parametrelerden birisidir. İri boyutlu parça atıklar genellikle inşaat sektöründe yapı elemanı olarak kullanılabilirken (beton agregası, suni mermer üretimi gibi), toz atıklar ise farklı endüstri dallarında (çimento, seramik, cam gibi) kullanılabilme imkânı bulmaktadır (Mehta, Paliwal & Sankhla, 2020; Ramos, Passalini & Holanda, 2023). Öte yandan, saf beyaz mermer tozu yüksek kalsiyum karbonat ($CaCO_3$) içeriği sayesinde mikronize kalsit ikamesi olarak birçok alanda (özellikle eczacılık, kâğıt, boya, plastik sektörü gibi) kullanılabilmektedir. Mermer atıklarının bu tip sektörlerde değerlendirilmesi için ilk ve en önemli koşul çok ince boyutlara öğütülmeleridir (Saboya, Xavier & Alexandre, 2007; Tressmann & ark., 2020; Liu & ark., 2023; Sellaf & Balegh, 2023).

Günümüzde, çok ince öğütme işlemi için değişik değirmen tipleri geliştirilmiştir. Bunlardan bazıları şunlardır: tamburlu değirmenler, karıştırmalı değirmenler, dönen silindirli (valsli) değirmenler, yüksek basınçlı merdaneli değirmenler, titreşimli değirmenler, jet tipi değirmenler, sarkaç değirmenler, çivili değirmenler vd. Bu değirmenlerin her birinin kendine özgü öğütme mekanizması, çalışma koşulları söz konusudur ve buna göre de avantajlı-dezavantajlı tarafları bulunmaktadır Aktarılan ortam prensibine göre çalışan geleneksel tamburlu değirmenler uzun öğütme süresi ve fazla enerji tüketimi ile birlikte geniş tane boyutu aralığında ürün verme eğilimindedirler. Ayrıca kritik bir tane boyutundan sonra (~75 µm) bu tip değirmenlerin öğütme verimi önemli ölçüde azalmaktadır (Hacıfazlıoğlu, 2009). Bununla birlikte, yüksek hızlı dinamik havalı ayırıcıların (separatör) gelişmesi ve yaygın olarak kullanılmaya başlaması özellikle talk, kalsit, barit gibi orta sertlikteki endüstriyel hammaddelerin bilyalı değirmenlerde çok ince boyutlara öğütülmesinde büyük bir etkiye sahip olmuştur. Bu ayırıcılar sayesinde, bilyalı değirmenlerde öğütülen hammaddelerin tane boyutları d_{97}=25µm (d_{50}=5 µm), hatta d_{97}=6 µm seviyesine kadar düşürülebilmiştir. Bu da daha ince ve homojen ürünler elde edilmesini sağlamıştır. Bilyalı değirmenlerin dinamik havalı ayırıcılarla birlikte kullanımı onları kuru mikronize öğütme uygulamalarında tercih edilen bir sistem haline getirmiştir.

Literatürde gezegensel, yörüngesel, planetary, planet değirmen olarak geçen bu değirmenler çok ince öğütme, mekanik aktivasyon, mekanik alaşımlama, mekano-kimyasal sentez, mekanik kaplama gibi farklı amaçlar için geliştirilmiş yüksek enerji değirmenleridir. Ayrıca metalürji, maden, seramik, kimya, biyoloji, eczacılık gibi çok geniş bir uygulama alanı bulunmaktadır. Adını çalışma prensibinden alan bu değirmenler, disk tablası ve bir veya daha fazla sayıda öğütme kabından (havan) oluşur (Şekil 1).

Şekil 1: Tek hazneli ve birden çok (iki ve dört) hazneli gezegensel değirmen tipleri

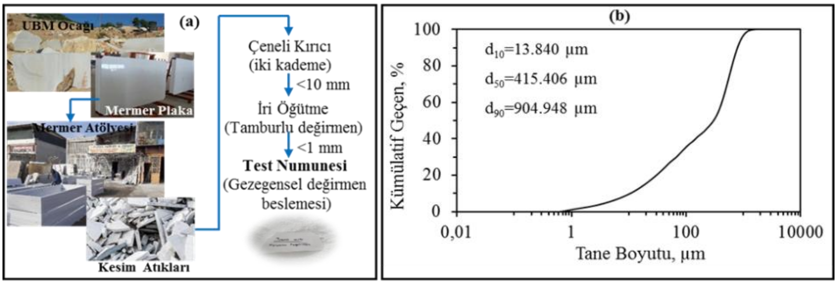
Gezegensel bilyalı değirmenin proses parametreleri ve öğütme mekanizması Şekil 2'de verilmiştir. Bu değirmenlerde, yüksek enerji yoğunluğu ve darbe kuvveti elde etmek için disk tablası ve havan zıt yönlerde yüksek hızda döndürülür. Bu iki dönüşün etkileşimiyle, bilyalar hem eksenel olarak döner hem de disk tablası üzerinde dairesel bir hareket çizer. Bu karmaşık hareket, bilyalara yüksek basınç ve darbe kuvveti uygular. Böylece diskin dönüşünün yarattığı merkezkaç kuvvetinin üzerine öğütme kabının kendi ekseni etrafında ters yönde dönmesinin yarattığı merkezkaç kuvvetinin de eklenmesiyle yüksek enerji yoğunluğu sağlanmış olmaktadır. Bu yüksek enerji yoğunluğu, basınç ve çok yüksek darbe kuvveti şeklinde bilyalara aktarılmaktadır. Ayrıca, yüksek santrifüj kuvvetin de etkisiyle birim zaman ve hacimde açığa çıkan enerji miktarının çok yüksek olması nedeniyle, klasik bilyalı değirmenlere göre daha kısa sürelerde çok ince boyutlu ve daha homojen malzeme elde etmek mümkün olmaktadır. Bu değirmenlerin öğütme mekanizması ve proses parametreleri arasındaki matematiksel ilişkiler literatürde geniş bir şekilde tartışılmıştır (Mio & ark., 2002; Fokina & ark., 2004; Baláž, 2008; Kakuk & ark., 2009; Burmeister & Kwade, 2013; Broseghini & ark., 2016). Gezegensel değirmenlerin birçok avantajları olmasına rağmen, diğer değirmenlerle kıyaslandığında kesikli öğütme yaparlar, yüksek maliyetlidirler, öğütme kapasiteleri düşüktür ve enerji yoğunluğu fazladır. Bu dezavantajlarından dolayı endüstriyel uygulamaları sınırlı olup, daha çok laboratuvar araştırmalarında, pilot ölçekli çalışmalarda, küçük hacimli üretimlerde, hassas malzeme hazırlama gibi işlemlerde kullanıldıkları bilinmektedir.



Şekil 2: Gezegensel bilyalı değirmenin proses parametreleri ve öğütme mekanizması (Kakuk & ark., 2009). (d_b: bilyaların çapı, m_b: bilyaların kütlesi, N_b: bilyaların sayısı, r_p: dönme eksenleri arasındaki mesafe, r_v: öğütme kabı (havan) yarıçapı, m_p: öğütme tozu kütlesi, ω_v: öğütme kabı (havan) dönüş hızı, ω_p: öğütme tablası(disk) dönüş hızı)

Çalışma Malzemesi ve Deney Prosedürü

Bu çalışmada kullanılan beyaz mermer atıkları, yerel bir mermer plaka işleme atölyesinden (Porga Mermer, Malatya/Türkiye) temin edilmiştir. İnce öğütme için gezegensel değirmende kullanılan çalışma numunesi Şekil 3(a) verilen işlem aşamaları takip edilerek hazırlanmıştır. Yaklaşık 15x20 cm ebatlarındaki prizmatik mermer parçaları ilk önce bir balyoz yardımıyla çeneli kırıcıya beslenebilecek boyuta kadar (~50 mm) kırılmıştır. Daha sonra, bir çeneli kırıcı kullanılarak (Fritsch Pulverisette 1 Model, Çene genişliği:65x65 mm) mermer parçaları iri ve ince kırma işlemiyle 10 mm'nin altına kırılmıştır. Çeneli kırıcıdan çıkan bu malzeme, son aşamada tamburlu bilyalı değirmende öğütülerek gezegensel değirmen üreticisi firmanın önerdiği besleme boyutunun altına getirilmiştir. Gezegensel bilyalı değirmen beslemesi olarak hazırlanmış bu malzemenin tane boyut dağılımı Şekil 3(b)'de verilmiştir. Buna göre, d_{90}=904,948, d_{50}=415,406 ve , d_{10}=13,840 µm olarak belirlenmiştir.



Şekil 3: Mermer atığının gezegensel değirmen beslemesi olarak 1mm altına indirgenmesi (a) besleme malzemesinin tane boyut dağılımı (b)

İnce Öğütme: Öğütme deneylerinde gezegensel bilyali değirmen (Fritsch Pulverisette 6 Mono Mill) ve 250 ml hacimli öğütme haznesi (akik havan) kullanılmıştır (Şekil 4(a)). Bu değirmen modeli tek hazneli olup, maksimum 650 rpm çalışma hızına sahiptir. Bu çalışmada kullanılan öğütme koşulları Çizelge 1'de verilmiştir. Tüm öğütme deneylerinde 0,25'lik sabit bir hacimsel bilya doluluk oranında çalışılmıştır. 2,5-5 ve 10 olmak üzere üç farklı bilya/toz oranı için sırasıyla 132, 66 ve 33 g numune kullanılmıştır. Öğütme işlemleri; 150-200-250-300-350 rpm değirmen dönüş hızlarında ve 7.5 dakikadan başlayarak 2 kat artışlarla 240 dakikaya kadar öğütme sürelerinde kuru olarak gerçekleştirilmiştir.

Tane Boyutu Analizi: Öğütülmüş malzemenin tane boyutu dağılımını (PSD) belirlemek için çeşitli yöntemler kullanılmaktadır.

En yaygın kullanılan yöntemlerden biri, kümülatif tane boyutu dağılım verilerini analiz etmektir. Bu yöntemde d_{90}, d_{50} ve d_{10} gibi istatistiksel parametreler kullanılır. Bu parametreler kümülatif tane boyutu dağılım eğrisinden elde edilir ve bir malzemenin tane boyutunun ne kadar geniş veya dar olduğunu gösterir. d_{90}: öğütülmüş malzemede bulunan taneciklerin %90'ının d_{90}'dan daha küçük olduğunu gösterir. d_{50} ise, malzemede bulunan taneciklerin %50'sinin d_{50}'den daha küçük olduğunu gösterir ve bu değere ortalama tane boyutu veya medyan tane boyutu da denilmektedir. d_{10}: öğütülmüş malzemdeki tanelerin %10'unun d_{10}'dan daha küçük olduğunu gösterir. Örneğin, d90 ve d10 değerleri birbirine yakınsa, malzemede bulunan taneciklerin boyutları birbirine yakındır ve malzeme nispeten homojendir. Tersi olarak d90 ve d10 değerleri arasındaki fark büyükse, malzemede bulunan taneciklerin boyutları geniş bir aralığa yayılır ve malzeme heterojendir.

Bu çalışmada, öğütme işlemiyle elde edilen tozların tane boyutu dağılımları için Şekil 4(b)'de görülmekte olan Mastersizer 2000 (Malvern Instruments Ltd., İngiltere) tane boyutu analiz cihazı kullanılmıştır. Bu cihaz, tane boyu ölçümü için lazer kırınım tekniğine dayanan Mie Saçılması veya Mie Modelini (Lock & Gouesbet, 2009) kullanmaktadır. Bu model, ışığın ortam içerisinde tane boyu etrafındaki hem kırılmasını hem de geçirgenliğini dikkate almaktadır. Yaklaşık 0,5 g numune, cihaza entegre edilmiş ölçüm numunesi hazırlama ünitesindeki 1 litrelik hücre içerisinde saf su ile 2500 rpm hızda karıştırılarak ölçüme hazır hale getirilmiştir. Bu sırada tanelerin homojen dağılımını sağlamak ve topakları dağıtmak için 0.05 M SHMP (Sodyum Hegza Meta Fosfat) çözeltisi süspansiyona eklenerek ultrasonik dalga ortamında 3 dakika boyunca karıştırılmıştır. Hazırlanmış bu sulu süspansiyon içindeki parçacıklar üzerinde ölçümler yapılmıştır. Ölçüm sonunda tane boyutu dağılım eğrileri ve "d" değerleri Mastersizer 2000 yazılımı üzerinden otomatik olarak elde edilmiştir.

Şekil 4: Öğütme işleminin gerçekleştirildiği gezegensel bilyalı değirmen ve öğütücü ortam bilyaları (a), tane boyutu analizinde kullanılan Mastersizer 2000 tane boyu analiz cihazı (b).

Tablo 1: Gezegensel bilyalı değirmen öğütme koşulları

Parametre	**Değeri**
Değirmen hızı	150, 200, 250, 300, 350 rpm
Öğütme süresi[1]	7.5, 15, 30, 60, 120, 240 dak
Bilya/Besleme oranı[2]	2.5, 5, 10
Bilya doluluk oranı[3]	0.25
Bilya türü, çapı ve yoğunluğu	Alubit bilya, 10 mm ve ~3,7 g/cm^3
Havan tipi, çapı ve hacmi	Agat havan, 70,5 mm ve 250 mL

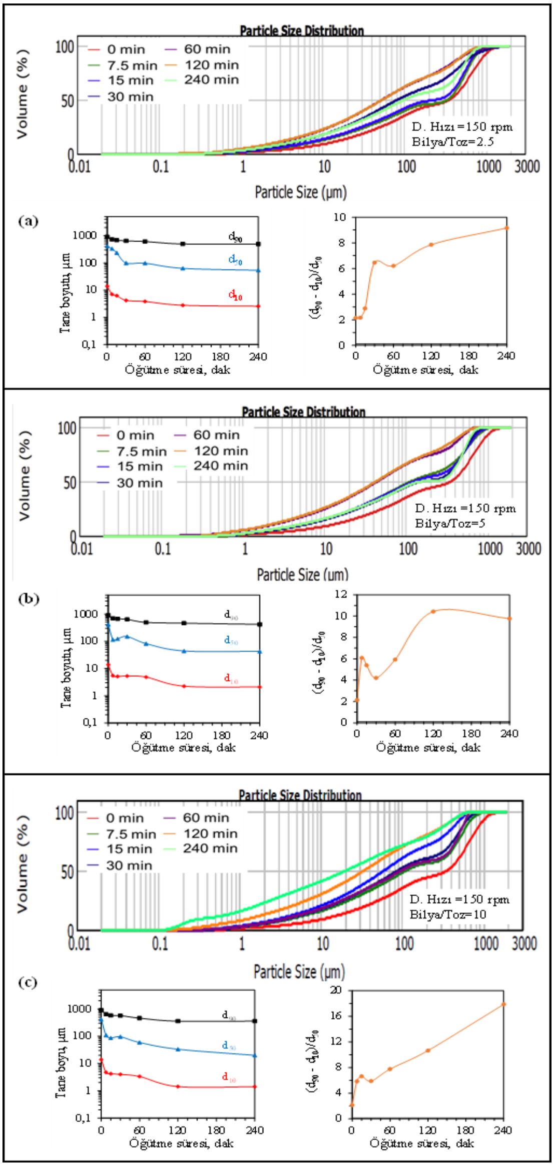
[1]Değirmen ısınmalarında fasılalı çalışma (15 dak start+5 dak stop)
[2]Kullanılan bilyaların toplam ağırlığı/öğütme numunesi ağırlığı
[3]Kullanılan bilyaların toplam hacmi/öğütme kabının hacmi

Öğütme Deney Sonuçları Ve Tartışma

Tane boyutu teknolojisinde, öğütülmüş taneli malzemenin tane boyutu genellikle kümülatif tane boyutu dağılım verileri kullanılarak belirlenmektedir. Diğer taraftan, Copelli & ark. (2018) tane boyutu için dört temel tanımlayıcı parametrenin yaygın olarak kullanıldığını vurgulamaktadır. Bu parametreler: d_{90}, d_{50}, d_{10} ve $(d_{90}-d_{10})/d_{50}$ dir. Söz konusu bu "d" değerleri doğrudan doğruya kümülatif geçen eğrisinden okunabilen istatistiksel parametrelerdir.

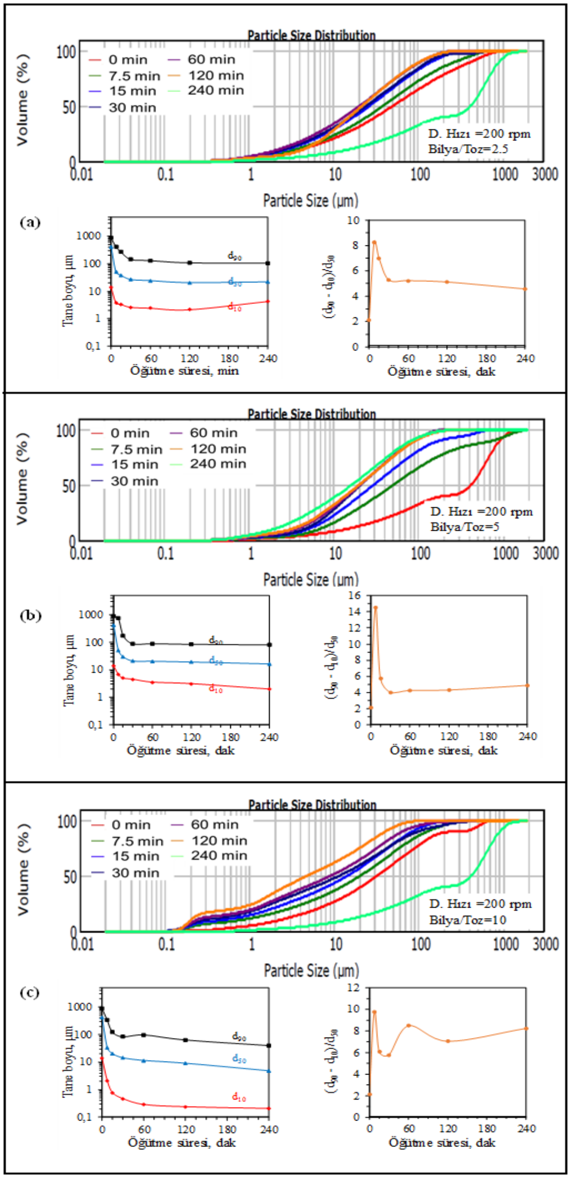
Bu çalışmada, öğütülmüş numunelerin kümülatif geçen eğrileri ve bu eğrilerden elde edilen “d” değerlerine ilişkin grafikler bir arada verilmiştir. Böylece tane boyutu verilerini farklı açılardan analiz edebilmek için daha anlaşılabilir ve karşılaştırılabilir grafik kombinasyonları oluşturulmuştur.

Gezegensel değirmende farklı öğütme koşullarında gerçekleştirilen öğütme işlemi sonucu elde edilen ürünlerin tane boyutu analiz sonuçları Grafik 1-5’te ayrı ayrı verilmiştir. En düşük değirmen hızı olan 150 rpm’de elde edilen sonuçlar Grafik 1(a, b, c)’de verilmiştir. Farklı öğütme sürelerinde elde edilen ürünlere ait kümülatif geçen eğrileri incelendiğinde, eğrilerin paralel bir şekilde birbirine yaklaştığı görülmektedir. Bu durum, öğütülmüş ürünlerin tane boyutunun başlangıç numunesi (değirmen beslemesi) boyutuna yakın olduğu anlamına gelmektedir. Ayrıca d_{90}, d_{50} ve d_{10} değerlerindeki değişime ilişkin grafikler dikkatlice izlendiğinde, tane boyutundaki esas azalmanın öğütmenin ilk evrelerinde gerçekleştiği açık bir şekilde görülmektedir. Yaklaşık 60 dakikadan daha uzun öğütme sürelerinde tane boyutunda az da olsa bir azalmanın devam ettiği görülmektedir. Bilya/toz oranındaki her üç durum için de benzer eğilim gözlenmektedir. Bununla birlikte, diğerlerine kıyasla en yüksek bilya/toz oranı (10) küçük de olsa daha ince ürün vermiştir. Örneğin, 15 dak öğütme süresi için 2,5-5 ve 10 bilya/toz oranlarında elde edilen ürünlerin ortalama tane boyutu (d_{50}) sırasıyla 235, 125 ve 100 µm olmuştur. Bu grup deneylerde en ince ürüne bilya/toz oranı 10 iken ulaşılmış olup, 120 dakika öğütme sonunda elde edilen bu ürünün d_{90}, d_{50} ve d_{10} değerleri sırasıyla d_{90}=350, d_{50}=30, d_{10}=1 µm olmuştur (Grafik 1(c)). Değirmene beslenen malzemenin “d” değerleriyle karşılaştırıldığında, 150 rpm gibi düşük değirmen hızının tane boyutunda önemli bir küçülme sağlamadığı, daha etkin bir öğütme işlemi ve çok daha ince boyutlu malzeme üretimi için daha yüksek değirmen hızlarına çıkılması gerektiği açık bir şekilde görülmektedir. Bilindiği gibi gezegensel değirmenlerde öğütme tane boyutunu etkileyen birçok çalışma parametresi vardır. Bunlar arasında değirmen hızı en önemli çalışma parametrelerinden birisidir. Hız arttıkça daha yüksek enerji yoğunluğu sağlanmakta, öğütme elemanlarının malzemeye çarpma sıklığı ve şiddeti de artmaktadır. Ayrıca, malzemenin öğütme kabı içinde daha fazla hareket etmesine de yol açmaktadır (Milin & Rajamani, 1997; Burmeister & Kwade, 2013).

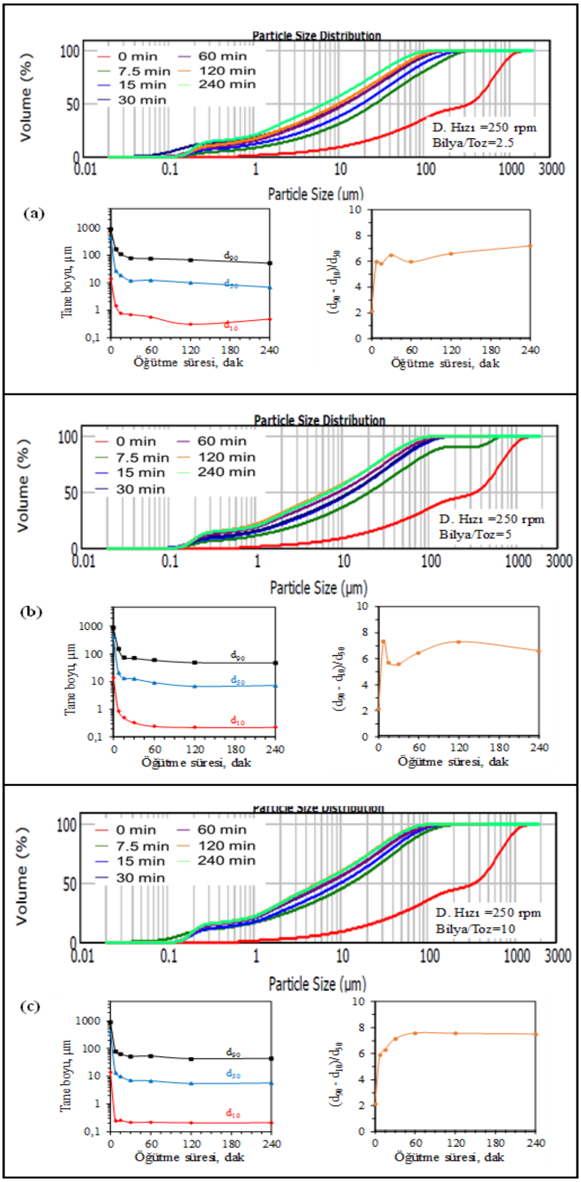


Grafik 1: 150 rpm değirmen hızında ve farklı bilya/toz oranında elde edilen ürünlerin tane boyutu dağılımı (a, b ve c sırasıyla bilya/toz oranı 2,5-5 ve 10 içindir)

Değirmen hızının 200 ve 250 rpm'e çıkarılmasıyla elde edilen sonuçlar Grafik 2 ve Grafik 3'te verilmiştir. Bu iki değirmen hızında elde edilen sonuçlar birbirine çok yakın olduğu için bir arada değerlendirilmiştir. Öğütme süresi arttıkça, kümülatif geçen eğrilerinin besleme numunesine ait ilk eğriden ayrılarak hafifçe sola doğru kaydığı görülmektedir. Bilindiği gibi, eğrilerdeki bu sola kayma tane boyutunda bir azalma olduğunu göstermektedir. 150 rpm'deki tane boyu grafikleriyle karşılaştırıldığında tane boyundaki bu gözle görülür azalma çok daha net olarak görülmektedir. Örneğin, 150 rpm değirmen hızı ve 15 dak öğütme süresi için 2.5, 5 ve 10 bilya/toz oranlarında elde edilen ürünlerin ortalama tane boyutu (d_{50}) sırasıyla 235, 125 ve 100 μm olarak verilmişti. Aynı öğütme süresi ve bilya/toz oranlarında d_{50} değerleri 200 rpm için yaklaşık 38, 30 ve 20 μm; 250 rpm için ise 19, 13 ve 10 μm olmuştur. Bu sonuçlar değirmen hızının ne kadar etkili olduğunu açık bir şekilde göstermektedir. Diğer bir sonuç ise, değirmen hızı arttıkça bilya/toz oranı etkisinin azalmaya başlamasıdır. Yukarıdaki d_{50} değerlerinin artan değirmen hızıyla birlikte giderek birbirine yaklaşması bu sonucu doğrulamaktadır. Ayrıca, Grafik 2(a, b, c) ve Grafik 3(a, b, c)'de verilen d değerlerine ilişkin grafiklere bakıldığında tane boyutundaki esas azalmanın öğütmenin ilk dakikalarında gerçekleştiği, 15. dakikaya kadarki keskin düşüşten sonra tane boyundaki azalmanın belirgin olarak yavaşladığı ve 30 dakikadan sonra neredeyse sabit kaldığı görülmektedir. Bu durum, öğütmenin etkin olduğu ya da öğütmenin tamamlandığı kritik bir öğütme süresinin varlığına işaret etmektedir. Öğütme hızı 200 ve 250 rpm için kritik öğütme süresinin 15-20 dakika olduğu kabul edilebilir. Daha uzun sürelerde öğütmenin etkinliği azalmaktadır. Bu durumun nedeninin; malzeme özellikleri ve öğütme koşullarına bağlı olarak gelişen birtakım mekanizmaların etkisiyle tanelerin topaklanması, ince tanelerin bilya yüzeylerine sıvanması, serbest tane miktarının azalması gibi oluşumların meydana gelmesinden kaynaklandığı düşünülmektedir. Nitekim, gezegensel değirmenlerde tane topaklaşması ve malzeme yapışması olaylarının yaygın olarak karşılaşılan problemlerden olduğu ve öğütme verimini önemli ölçüde etkilediği bilinmektedir (Guzzo & ark., 2020; Kong & ark., 2023).



Grafik 2: 200 rpm değirmen hızında ve farklı bilya/toz oranında elde edilen ürünlerin tane boyutu dağılımı (a, b ve c sırasıyla bilya/toz oranı 2,5-5 ve 10 içindir).



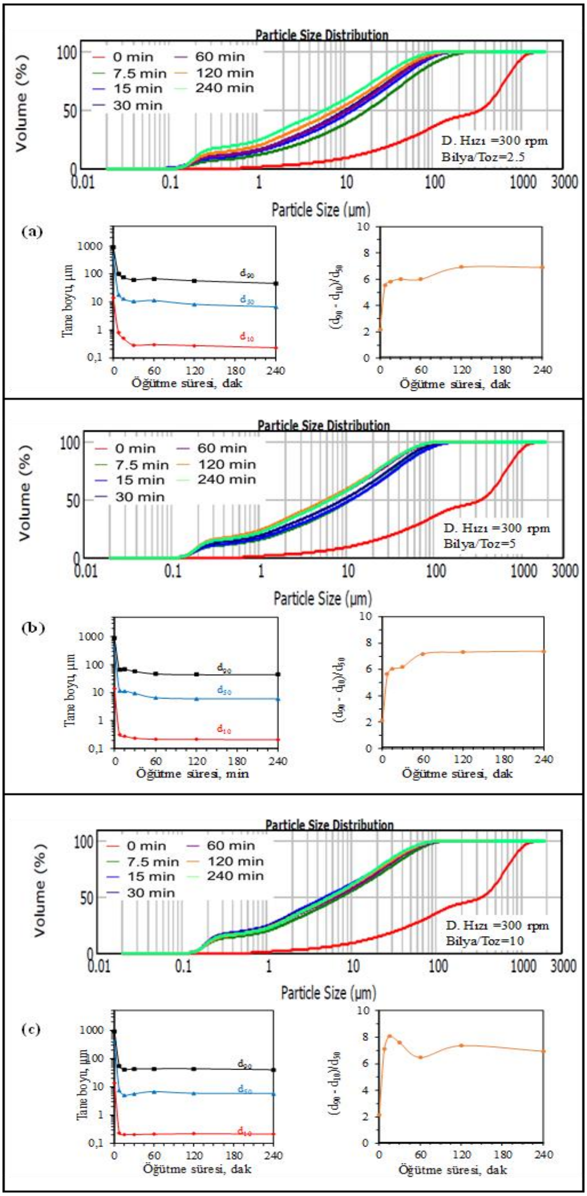
Grafik 3: 250 rpm değirmen hızında ve farklı bilya/toz oranında elde edilen ürünlerin tane boyutu dağılımı (a, b ve c sırasıyla bilya/toz oranı 2,5-5 ve 10 içindir).

Bu grup deneylerde en ince ürüne değirmen hızı=250 rpm, bilya/toz oranı=10 ve öğütme süresinin=15 dakika olduğu öğütme koşulunda ulaşılmış olup, elde edilen ürünün d değerleri d_{90}=60, d_{50}=8, d_{10}=0,2 µm olmuştur. Sonuçlar incelendiğinde, d_{90} ve d_{10} değerleri arasındaki farkın nispeten büyük olduğu görülmektedir. Söz konusu bu "d" değerleri arasındaki farkın açılması, malzemede bulunan taneciklerin boyutlarının daha geniş bir aralığa yayıldığını ve malzemenin heterojen dağılım gösterdiğine işaret etmektedir.

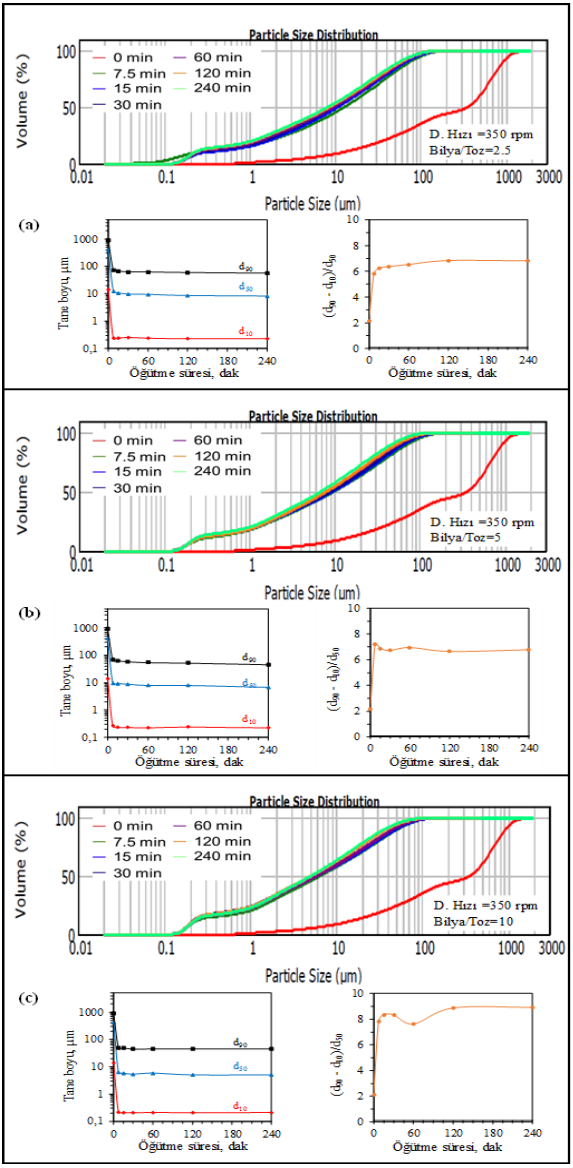
Değirmen hızının biraz daha artırılarak önce 300 ve daha sonra 350 rpm'e ulaşmasıyla elde edilen öğütme sonuçları sırasıyla Grafik 4 ve Grafik 5'te gösterilmiştir. Tane boyutu verileri karşılaştırmalı olarak incelendiğinde aşağıdaki bulgulara ulaşılmıştır. Her iki değirmen hızında da öğütme işleminin ilk dakikalarında tane boyutunun keskin bir şekilde azaldığı ve kritik öğütme süresinin yaklaşık 10 dakikaya düştüğü görülmektedir. Bir önceki değirmen hızlarındaki sonuçlarla kıyaslandığında, değirmen hızı arttıkça kritik öğütme süresinin bariz bir şekilde azaldığı görülmektedir. Ayrıca tüm öğütme sürelerinde tane boyutu dağılım eğrilerinin neredeyse çakışık duruma geldikleri görülmektedir. Bunun anlamı, elde edilen ürünlerin tane boyutlarının birbirine çok yakın olduğudur. Hatta 30 dakikadan daha uzun öğütme sürelerinde elek altı eğrilerinin göreceli olarak iri boyuta kaydığı da olmuştur. Normalde öğütme süresi arttıkça tane boyutunda azalma beklenirken bunun tersine olması, tane topaklaşmasıyla açıklanacak bir durumdur. Zaten bu grup deneylerde öğütmeyi engelleyen tanelerin topaklaşması, havan duvarlarında ve bilya yüzeylerinde kabuk oluşumu çok daha belirgin bir şekilde gözlemlenmiştir. Özellikle 350 rpm'de bahsedilen bu olaylar çok daha erken zamanda oluşmaya başlamış, havan tabanında daha fazla olmak üzere iç çeperlerde kabuk kalınlığı belirgin bir şekilde artmıştır.

Bu grup öğütme deneylerinden elde edilen diğer bir bulgu, kümülatif geçen eğrilerinin alt uçlarında meydana gelen kıvrılmanın(ondülasyon) iki modlu tane boyut dağılımının meydana geldiğini göstermesidir. İki modlu (bimodal) tane boyutu dağılımı, bir malzemede iki tane boyutu piki veya modu olduğu ve malzemenin iki farklı boyut aralığında önemli miktarda taneciğe sahip olduğu anlamına gelir. Bu durumun, ayrışma ve/veya aglomerasyon gibi işlemlerden kaynaklandığı düşünülmektedir. Bu konuyla ilgili güncel bir çalışmada (Guzzo & ark., 2020), ultra ince öğütmenin kireçtaşı, dolomit gibi endüstriyel minerallerin işlenmesinde temel işlemlerden olduğunu ancak 10 mikronun altındaki tanelerin yüksek yüzey reaktifliğinden dolayı tane-tane etkileşimi sırasında oluşan aglomerasyonunun önemli bir sorun olduğunu vurgulanmaktadır. Guzzo & ark. (2020), aglomerasyonun oluşmaya başladığı anda elde edilen minimum parçacık boyutunu, görünür öğütme sınırı olarak tanımlamışlardır. Bu sınır aynı zamanda kritik öğütme süresini de belirlemiş olmaktadır. Dolayısıyla 300 ve 350 rpm gerçekleştirilen bu grup deneyler için aglomerasyon oluşumunun başladığı kritik öğütme süresinin (ya da efektif öğütmenin bitiş süresi) ilk 10-15 dakika olduğu söylenebilir. Sonuç olarak, değirmen hızı kademeli olarak arttıkça etkin öğütme süresi buna paralel olarak kısalmış olmaktadır. Bu beklenen bir durumdur. Çünkü, değirmenlerde yüksek hızlara çıkıldığında biyeler ve taneler arasındaki çarpışma sıklığı önemli ölçüde artmakta, taneler daha kısa sürede öğütülmektedir (Panigrahi & ark., 2018).

Değirmen hızından etkilenen bir diğer değişken bilya/toz oranındaki değişimdir. 150-250 rpm gibi düşük hızlarda bilya/toz oranındaki artışın tane boyutu üzerinde belirgin bir etkiye sahip olduğu gözlemlenmişken, 300-350 rpm gibi nispeten daha yüksek değirmen hızlarında bilya/toz oranının etkisi yok denilecek kadar azalmıştır. Örneğin, 300 rpm değirmen hızı ve 7,5 dak öğütme süresi için 2.5, 5 ve 10 bilya/toz oranlarında elde edilen ürünlerin ortalama tane boyutu (d_{50}) sırasıyla 17, 12, 8 µm olarak okunmaktadır (Grafik 4(a, b, c)). Aynı öğütme koşullarında ancak 350 rpm için ise (d_{50}) değerleri 13, 10, 7 µm bulunmuştur (Grafik 5(a, b, c)). Bu değerler arasında anlamlı bir farklılığın oluşmadığı ortadadır. Sonuç olarak, 300 ve 350 rpm'de gerçekleştirilen öğütmeler tane boyutu açısından birbirine çok yakın sonuçlar vermiştir. Bununla birlikte en ince tane boyutuna; değirmen hızı=350 rpm, öğütme süresi=7,5 dak ve bilya/toz =10 koşullarında ulaşılmıştır. Bu öğütme koşullarında elde edilen ürünün ortalama d değerleri şu şekildedir: d_{90}=45 µm, d_{50}=5 µm ve d_{10}=0,2 µm.



Grafik 4: 300 rpm değirmen hızında ve farklı bilya/toz oranında elde edilen ürünlerin tane boyutu dağılımı (a, b ve c sırasıyla bilya/toz oranı 2,5-5 ve 10 içindir).



Grafik 5: 350 rpm değirmen hızında ve farklı bilya/toz oranında elde edilen ürünlerin tane boyutu dağılımı (a, b ve c sırasıyla bilya/toz oranı 2,5-5 ve 10 içindir).

Sonuçlar

Bu çalışma, farklı amaçlar için kullanılmak üzere mermer atıklarının gezegensel bilyalı değirmende ince boyuta öğütme olanağı araştırılmıştır. Çalışmadan elde edilen genel sonuçlar aşağıda maddeler halinde verilmiştir:

Gezegensel bilyalı değirmende gerçekleştirilen öğütme deneylerinde değirmen hızı, öğütme süresi ve bilya/toz oranı başlıca çalışma parametreleri olarak incelenmiştir. Tane boyutu analizi sonuçlarına göre, öğütme parametrelerinden özellikle değirmen hızı tane boyutu üzerinde diğerlerine göre belirleyici etkiye sahip olmuştur. Ayrıca değirmen hızı arttıkça etkin öğütme süresinin belirgin olarak kısaldığı görülmüştür.

Değirmen hızına bağlı olarak elde edilen en ince ürünlerin tane boyutu değerleri şu sonuçları vermiştir: 150 rpm için d_{90}=350, d_{50}=30, d_{10}=1 μm; 200 rpm için d_{90}=100, d_{50}=15, d_{10}=0,7 μm; ; 250 rpm için d_{90}=60, d_{50}=8, d_{10}=0,2 μm; 300 ve 350 rpm için ise d_{90}=45, d_{50}=5, d_{10}=0,2 μm.

Tane boyutundaki esas küçülmenin genel olarak öğütme işleminin ilk evrelerinde gerçekleştiği görülmüştür. Özellikle 300-350 rpm aralığındaki hızlarda öğütmenin büyük oranda tamamlandığı kritik öğütme sürenin 10 dakika civarlarında olduğu tespit edilmiştir.

Çok uzun öğütme sürelerinde tane aglomerasyonuna bağlı olarak tanelerin bilya yüzeyine sıvanması, havan duvarlarında gittikçe artan kabuklaşma gibi öğütmeyi engelleyen durumlara karşılaşılmaktadır.

Düşük değirmen hızından nispeten daha yüksek değirmen hızlarına çıkıldığında, tane boyutu eğrilerinde tek modlu dağılımdan iki modlu dağılıma geçişler olduğu görülmüştür.

Öğütme deneyleri sonucunda ancak 45 μm'nun altında (d_{90}<45 μm) bir ürün elde edilebilmiştir. Bu boyutun altında ultra-ince ya da mikronaltı/submicron malzeme (<1 μm) elde edilememiştir.

Katkı Belirtme

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CHAPTER IV

Sondaj Teknolojisi ve Uygulamaları: Geçmişten Geleceğe Bir Bakış

Onur Eser KÖK[1]

1. GİRİŞ

Sondaj, yeraltı kaynaklarının tespiti, araştırılması ve üretimi gibi amaçlar için gerçekleştirilen bir kavram olarak tanımlanmaktadır. Yeryüzünden yeraltına yapılan sondaj işlemleri ile doğal kaynaklardan faydalanılması, jeolojik yapıların incelenmesi, yeraltı su seviyelerinin belirlenmesi ve çevresel etki incelemelerinin yapılması amaçlanmaktadır. Bu sebeple enerji konusunda oldukça yüksek öneme sahiptir (Teodoriu & Bello, 2021).

Başarılı bir sondaj işlemi lokasyon seçimi, sondaj öncesi planlama, sondaj, veri toplama ve analiz ve sonuçların değerlendirilmesi gibi birkaç farklı aşamanın birleşimi ile yapılabilmektedir. Her aşama ayrı öneme sahip olmakla birlikte sondaj işlemini etkilemektedir. Her sondaj işlemi için farklı yöntemler kullanılmakta ve bu yöntemlerin avantaj ve dezavantajları

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bulunmaktadır. Dolayısıyla sondaj işlemi öncesinde planlama aşamasının dikkatle yapılması gerekmektedir (Wang & Guang, 2020).

Günümüzde artan enerji ihtiyacı ve tüketim artışı incelendiğinde sondaj teknolojisinin önemi giderek artmaktadır. Enerji talebi, çevresel faktörler ve sürdürülebilir kaynak kullanımı ile doğrudan ilişkili olan sondaj kavramı enerji üretimi için ön plana çıkmaktadır. Enerji tüketimi ve doğal kaynakların kullanımı sürekli artarken, fosil yakıtların tükenmesi ve yenilenebilir enerji kaynaklarının önem kazanması, sondaj teknolojisinin geliştirilmesi ve optimize edilmesi gerekliliğini ortaya çıkarmıştır (Vincké & Mabile, 2004). Özellikle, petrol, doğal gaz ve kömür gibi fosil yakıtlar ile birlikte jeotermal kaynaklar gibi enerji kaynaklarının tespiti ve üretimi için geliştirilmiş olan sondaj yöntemleri, enerji sektöründe hayati bir rol oynamaktadır. Ayrıca, sondaj teknolojisi enerji sektörü haricinde madencilik, su kaynaklarının verimli kullanımı ve çevresel araştırma ile incelemeler gibi birçok farklı alan için de önemini korumaktadır (Xinming, 2014; Guan, Chen & Liao, 2021). Farklı uygulama alanları farklı sondaj işlemlerini ön plana çıkarmakta ve multidisipliner mühendislik işbirlikleri sağlamaktadır.

Yapılan bu çalışma, sondaj teknolojisinin tarihsel gelişimini, uygulama alanlarını, ekipman ve yöntemlerini, güncel teknolojilerini ve gelecekteki perspektiflerini detaylı olarak ele almayı amaçlamaktadır. Bu sayede sondaj teknolojisinin önemi ve farkındalığının artması hedeflenmektedir.

2. TARİHSEL GELİŞİM

Sondaj teknolojisi, tarihsel olarak insanlık tarihine yakın durumdadır. Antik çağlarda su kaynaklarının keşfi ve kullanımı amacıyla ilkel anlamda ilk sondaj teknikleri kullanılmıştır. Bu tekniklerde basit delici el aletleri ve bambu çubuklar ile su keşifleri yapılmış ve kullanılmıştır. Örneğin, Mısır'da M.Ö. 3000 yıllarında kullanılan bambu çubuklar ve delici uçlar ile yapılan sondaj işlemleri ilkel dönem sondaj uygulamalarına örnek olarak gösterilebilir. Bu teknikler genellikle yer altındaki su ve tuz kaynaklarının çıkarılmasını amaçlamaktaydı. İlerleyen zaman ile beraber, bu teknikler daha gelişmiş ve sistematik hale gelerek, mineral kaynakları ve enerji üretimi için sondaj işlemleri gerçekleştirilmesine olanak sağlamıştır (Gwinnett & Gorelick, 1998).

19. yüzyıl, sondaj teknolojisi açısından oldukça büyük bir öneme sahiptir ve önemli dönüşümler ile gelişimler geçirdiği bir dönemdir. Endüstriyel Devrim ile birlikte, kömür, petrol ve doğal gaz gibi fosil yakıtlara bağlı artan enerji talebi, sondaj yöntemlerinin hızla geliştirilmesine olanak sağladı. Özellikle, 1859 yılında Edwin Drake tarafından Amerika Birleşik Devletleri'nde açılan ilk petrol kuyusu ile modern petrol endüstrisinin temelinin atıldığı kabul edilmektedir. Bu kuyunun açılması ve sonrasında ilerleyen sondaj teknolojisi ile sondajın ekonomik değerinde artış meydana geldi ve daha fazla yatırımın yapılmasına olanak sağlandı. Bu dönemde, daha güçlü ve dayanıklı sondaj ekipmanları geliştirildi ve mühendisliksel olarak farklı teknikler geliştirildi. Örneğin, buhar gücüyle çalışan matkaplar, daha derin ve daha etkili sondaj işlemleri yapabilmek için kullanıldı. Ayrıca, sondaj yöntemleri de çeşitlenerek, dikey sondajın yanı sıra yatay ve yönlendirilmiş sondaj teknikleri de kullanılmaya başlandı. Bu sayede, sondajın daha verimli ve düşük maliyetli yapılabilmesine imkan sağlandı (Gerali, 2019).

20. yüzyılın ortalarından sonra, sondaj teknolojisindeki önemli teknolojik ilerlemeler devam etti. Uzaktan izleme, otomasyon sistemleri, veri analizi ve dijital teknolojilerin entegrasyonu gibi etkenler ile birlikte sondaj işlemleri daha güvenli ve profesyonel bir şekilde gerçekleştirilmeye başlandı. Özellikle, bilgisayar destekli mühendislik ve simülasyon yazılımları, sondaj faaliyetlerinin planlanması ve uygulanmasında önemli katkılar sağladı. 1960'larda, offshore olarak ifade edilen açık deniz sondaj teknolojileri geliştirilerek, denizlerde yer alan petrol ve gaz rezervleri keşfedilmeye ve üretime kazandırılmaya başlandı. Bu gelişmeler, küresel enerji pazarının dinamiklerini değiştirdi ve deniz altı sondaj teknolojisinin önemi giderek artış gösterdi. Ayrıca, jeotermal enerji kaynaklarının keşfi ve kullanımı da bu yüzyılda hız kazandı. 1970'lerde ve 1980'lerde, sondaj teknolojilerinde uluslararası

güvenlik standartlarının artması ve çevresel etki değerlendirmelerinin önemi gündeme gelmeye başladı. Ayrıca, çevre dostu sondaj yöntemleri ve atık yönetim sistemleri geliştirildi (Mohammed, Okeke & Abolle-Okoyeagu, 2012).

Günümüzde ise, sondaj teknolojisi hızla evrim geçirmeye devam etmektedir. Dijitalleşme ile yapay zeka ve otomasyon sistemleri sondaj süreçlerinin daha etkin ve güvenli bir şekilde gerçekleştirilmesine olanak sağlamaktadır. Yenilenebilir enerji kaynaklarına olan ilgi artmakta ve özellikle jeotermal sondaj teknolojileri günümüzde giderek gelişmektedir. Jeotermal enerji haricinde diğer alternatif enerji kaynaklarının keşfi ve kullanımı için yeni sondaj yöntemleri geliştirilmektedir. Bu bağlamda, sondaj teknolojisinin gelecekteki gelişimi, sürdürülebilir enerji politikaları ve çevre dostu uygulamalar ile ilişkisi giderek artmaktadır (Baoping & Huinian, 2023).

3. UYGULAMA ALANLARI

Sondaj teknolojisi, çeşitli endüstrilerde ve uygulama alanlarında yaygın olarak kullanılmaktadır. Ayrıca, enerji sektöründe en yaygın ve kritik uygulama alanlarından biridir. Başlıca olarak petrol, doğal gaz ve jeotermal enerji kaynaklarının keşfi, araştırılması ve çıkarılması konularında uygulamalar bulunmaktadır.

Petrol ve doğal gaz endüstrisi, sondaj teknolojisinin en yoğun kullanıldığı alanlardan biridir. İlk petrol kuyusunun açılmasıyla birlikte, bu alandaki sondaj faaliyetleri hız kazanmış ve dünya genelinde büyük bir endüstri haline gelerek hızla gelişmiştir. Dikey ve yatay sondaj yöntemleri, derin deniz ve karasal alanlarda petrol ve doğal gaz rezervlerinin keşfi için kullanılmaktadır. Ayrıca, belirli rezervlere ulaşmak için özel olarak tasarlanmış yönlü sondaj gibi teknikler de bulunmakta ve özellikle karmaşık jeolojik yapılar altında büyük bir avantaj sağlamaktadır (Hossain & Al-Majed, 2015).

Jeotermal enerji, yer altındaki sıcak su ve buhar kaynaklarının kullanımıyla elde edilmektedir. Sondaj, jeotermal kaynakların keşfi ve kullanımı için önemli ve başlıca araçlardan biridir. Jeotermal enerji santrallerinde, yeraltındaki rezervlere ulaşmak için özel sondaj teknikleri kullanmaktadır. Bu, enerji üretimi konusunda yenilenebilir enerji kaynaklarına geçişte önemli bir rol oynamaktadır (Capuano, 2024).

Madencilik alanında özellikle altın, gümüş, bakır ve diğer kıymetli madenlerin çıkarılması için çeşitlisondaj teknikleri kullanılır. Sondaj, potansiyel maden sahalarının keşfi ve rezerv tahminleri için gerekli verilerin toplanmasında kritik bir rol oynamaktadır. Ayrıca, madencilik projelerinde, yeraltı yapısının incelenmesi için sondaj teknolojisinden faydalanılmaktadır. Jeolojik veriler, madenin değerini belirlemek ve üretim yöntemlerini planlamak için kritik öneme sahiptir. Özellikle, çevresel etki değerlendirmeleri ve sürdürülebilir uygulamalar açısından, bu verilerin doğru bir şekilde toplanması büyük bir önem taşımaktadır (Hrehoca, & ark., 2012).

Yeni yapı projeleri için, zemin etüdü amacıyla sondaj işlemleri yapılmaktadır. Yapıların temel tasarımı, güvenlik ve dayanıklılık açısından kritik bir faktördür. Bu sebeple sondaj işlemleri, zemin etüdü ve temel derinliği gibi bilgilerin elde edilmesini sağlar ve güvenli yapıların oluşturulmasında etkilidir (Austin, 2012).

Yol, köprü ve diğer altyapı projeleri için, yeraltı su seviyeleri ve zemin özelliklerinin belirlenmesi amacıyla sondaj işlemleri yapılmaktadır. Elde edilen veriler ise projelerin planlanması ve uygulanması sürecinde önemli rol oynamaktadır (Austin, 2012).

Tarım, sanayi ve içme suyu ihtiyacını karşılamak amacıyla yer altı su kaynaklarına ulaşmak için sondaj işlemleri yapılmaktadır. Su kuyuları, yer altındaki su kaynaklarının sürdürülebilir bir şekilde kullanılması için oldukça önemlidir. Bu sebeple sondaj işlemleri ile sürdürülebilirliği sağlanmaya çalışılmaktadır (Austin, 2012).

Yer altı su seviyelerinin izlenmesi ve su kaynaklarının yönetimi açısından da sondaj işlemleri önemli durumdadır. Sondajlar ile yeraltı su seviyelerinin belirlenmesi ve izlenmesi yapılabilmektedir. Böylece su kaynaklarının sürdürülebilir kullanımına olanak sağlanmaktadır (Shen, Bai & Standifird, 2012).

Sondaj işlemleri, yer altı ekosistemlerinin araştırılması ve korunması için de kullanılmaktadır. Özellikle, biyolojik çeşitliliğin korunması ve doğal kaynakların sürdürülebilir yönetimi açısından, bu araştırmalar büyük bir öneme sahiptir. Bu sayede ekolojik araştırmalar için de sondaj faaliyetleri önem arz etmektedir.

4. EKİPMAN VE YÖNTEMLER

Sondaj işlemlerinin verimliliği ve güvenliği için birçok sondaj ekipmanı kullanılmaktadır. Bu ekipmanlar, sondaj türüne ve araştırma faaliyetine göre değişiklik göstermektedir, ancak genel olarak sondaj makineleri, matkaplar, sondaj boruları ve sirkülasyon elemanları başlıca ekipmanlar olarak öne çıkmaktadır.

Sondaj Makineleri, farklı sondaj yöntemlerine (karot, darbeli, döner) ve uygulamalarına uygun olarak tasarlanmış büyük ve kompleks yapılı makinelerdir. Bu makineler, sondaj işleminin temelini oluşturur ve matkapları döndürerek delme işlemini gerçekleştirir (Assaad & LaMoreaux, 2004).

Matkaplar, sondaj işlemlerinde kullanılan en önemli ekipmanlardan biridir. Matkaplar, jeolojik formasyonları delerek hem örnek almak hem de sondajın ilerlemesini sağlamak için kullanılır. Farklı jeolojik koşullara göre çeşitli matkap türleri bulunmaktadır.

Sondaj Boruları, sondaj işlemi esnasında kullanılan tij, tübing, ağırlık boruları (HWDP) gibi borulara verilen genel isim olarak tanımlanmaktadır. Bu borular formasyonu delme işlemi sırasında matkapları destekler ve delinen alanı stabilize eder. Sondaj borularının dayanıklılığı yapılan sondaj işleminin gereksinimlerini karşılaması oldukça önemlidir. Genellikle çelik veya alüminyumdan üretilirler ve uluslararası standartları sağlamaları gerekmektedir (Assaad & Lamoreaux, 2004).

Sirkülasyon Elemanları, sondaj işlemi esnasında sondaj akışkanının kuyu temizliğini sağlamasını ve hem yüzeyde hem de kuyu içinde kesintilerin taşınması ve delme işleminin devam etmesini sağlayan tüm ekipman ve malzemeleri ifade etmektedir (Samuel, 2007).

Sondaj yöntemleri, jeolojik formasyon koşullarına, hedeflenen derinliğe ve elde edilmek istenen verilere ve analizlere göre değişiklik göstermektedir. Ancak, başlıca sondaj yöntemleri olarak dikey, yatay ve yönlendirilmiş sondaj türleri öne çıkmaktadır.

Dikey sondaj, sondaj işleminin yer yüzeyine dik bir açıyla gerçekleştirildiği yöntem olarak tanımlanmaktadır. Genellikle petrol, doğal gaz ve jeotermal kuyularının açılmasında kullanılmaktadır. Dikey sondaj, basit ve doğrudan bir yöntem olmasına rağmen, derinlik artırıldıkça farklı düzeyde zorlukları bulunmaktadır (Samuel, 2007).

Yatay sondaj, sondaj işleminin, yer yüzeyine paralel veya yatay bir açıyla gerçekleştirildiği yöntem olarak tanımlanmaktadır. Yatay sondaj yöntemi özellikle deniz altı petrol ve doğal gaz rezervlerinin keşfi ve üretiminde yaygın olarak kullanılmaktadır. Yatay sondaj, belirli bir alanda daha fazla rezervin keşfedilmesine olanak tanır ve çevresel etkiyi azaltmak gibi önemli avantajları bulunmaktadır (Samuel, 2007).

Yönlendirilmiş sondaj yöntemi, belirli bir hedef derinliğe ulaşmak için sondajın çeşitli açılarda yönlendirilerek gerçekleştirildiği bir uygulama olarak tanımlanmaktadır. Bu yöntem, karmaşık jeolojik formasyon yapılarında veya hassas üretim noktalarına ulaşmak için özel bir yöntem olarak kullanılmaktadır. Yönlendirilmiş sondaj, yüksek teknoloji gerektiren bir süreç olmaktadır ve genellikle özel sondaj ekipmanları kullanılarak gerçekleştirilir (Samuel, 2007).

Bahsi geçen sondaj yöntemleri değerlendirildiğinde her bir sondaj yönteminin farklı uygulama alanları için özelleştirilmiş olarak kullanıldığı görülmektedir. Petrol, doğal gaz ve jeotermal kaynak sondajları için genellikle dikey ve yatay sondaj yöntemleri kullanılmaktadır. Yönlendirilmiş sondaj ise genel olarak rezervlerin yerini belirlemek gibi keşif amaçlı uygulanmaktadır. Farklı uygulama alanlarına göre seçilen ekipman ve yöntemler, sondaj işlemlerinin verimliliğini artırmakta ve çevresel etkilerin asgari düzeyde olmasına yardımcı olmaktadır (Hasan, Zhao & Jiang, 2017; Shubin, Hongjian & Heng, 2020).

5. GELECEK EĞİLİMLERİ VE GÜNCEL TEKNOLOJİLER

Sondaj teknolojisi, geçmişten günümüze kadar sürekli gelişim göstermekte ve yeni trendler ortaya çıkmaktadır. Son yıllarda dijital teknolojilerin sondaj sektörüne entegrasyonu hız kazanmış ve sondajlarda başarı oranı giderek artmıştır. Büyük veri analitiği, sondaj süreçlerinin daha etkin bir şekilde yönetilmesine olanak tanımaya başlamıştır. Jeolojik verilerin analiz edilmesi, yüksek doğrulukta rezerv tahminleri yapılmasına imkan sağlamış ve olası riskleri düşürmüştür. Sondaj makinelerinin uzaktan izleme ve kontrol sistemleri ile donatılması ile birlikte sondaj operatörleri bu makineleri daha etkili ve verimli bir şekilde yönetebilmektedir. Bu sistemler, gerçek zamanlı verilerin izlenmesine ve hızlı karar alınmasına olanak sağlamıştır. Otonom sondaj makineleri, insan müdahalesine ve becerisine ihtiyaç duymadan sondaj işlemlerini gerçekleştirebilmektedir. Bu durum, iş gücü maliyetlerini azaltırken, çalışma güvenliğini de artırmaktadır. Özellikle tehlikeli ve ulaşım zorluğu olan bölgelerde bu teknolojilerin kullanımı büyük avantajlar sağlamaktadır (Lehmann & ark., 2017).

Çevresel etkiler ve sürdürülebilirlik kavramı, günümüz sondaj teknolojisinde giderek önem kazanmaktadır. Jeotermal enerji gibi yenilenebilir enerji kaynaklarının keşfi, geliştirilmesi ve üretimi için güncel sondaj yöntemleri yaygın olarak kullanılmaktadır. Bu durum, fosil yakıtlara olan bağımlılığı azaltmakta ve çevresel sürdürülebilirliği de artırmaktadır. Sondaj süreçlerinde oluşan atıkların yönetimi ve geri dönüşümü konusunda yeni stratejiler de geliştirilmektedir. Bu durum, çevresel etkileri azaltmanın yanı sıra maliyetleri de minimum seviyeye getirmeyi amaçlamaktadır (Lehmann & ark., 2017).

Açık deniz sondajları, petrol ve doğal gaz kaynaklarının keşfi ve üretimi için oldukça önemli bir alan oluşturmaktadır. Gelişen teknolojiler ile birlikte açık deniz sondaj işlemleri, daha derin sularda, okyanuslarda ve zorlu koşullarda rahatlıkla gerçekleştirilebilmektedir. Derin deniz sondajlarında kullanılan özel teknolojiler sayesinde 5.000 metre derinliğe kadar başarılı sondajlar yapılabilmektedir. Bu tür sondajlar yüksek teknoloji gerektirdiği için geleneksel sondaj yöntemlerine göre daha yüksek maliyetler ve riskler içermektedir. Dolayısı ile açık deniz sondajlarında kullanılan malzeme ve ekipmanlar, zorlu koşullarına dayanacak şekilde tasarlanmıştır. Açık deniz sondajlarında kullanılan yenilikçi yöntemler, sondaj çalışmalarını daha güvenli ve verimli hale getirmiştir (Cheatham, 1983).

Sondaj teknolojisinin geleceğinde, farklı eğilimler ön plana çıkmaktadır. Yapay zeka gibi araçlar, sondaj süreçlerinin optimize edilmesinde ve karar alma süreçlerinin hızlandırılmasında olanaklar sağlamaktadır. Makine öğrenimi algoritmaları, jeolojik verilerin yüksek doğrulukla analizinde ve rezerv tahminlerinde başarılı sonuçlar sağlayabilmektedir. Gelecekte, daha karmaşık jeolojik yapılar altında kaynaklara ulaşım için özel sondaj yöntemleri de geliştirilmeye çalışılmaktadır. Bu durum, zorlu sondaj koşullarında çalışabilme imkanı sağlayarak yeni rezervlerin keşfine ve üretimine olanak tanıyacaktır (Islam & Hossain, 2020). Ayrıca, sürdürülebilirlik ve çevresel sorumluluk gibi kavramlar da sondaj endüstrisinin geleceğinde daha fazla önem kazanacaktır. Çevre dostu uygulamalar ve teknolojiler, doğal kaynakların daha sürdürülebilir bir şekilde yönetilmesine katkıda bulunacaktır.

6. SONUÇ

Sondaj teknolojisi, doğal kaynakların keşfi, üretimi ve kullanımı için oldukça önemli bir alan olmaya devam etmektedir. Sondaj teknolojisi, tarihsel süreçte önemli değişimler geçirmiştir. İlk uygulamalar, ilkel çağlarda basit yöntemlerle gerçekleştirilirken, günümüzde gelişmiş makine ve ekipmanlar, dijital teknolojiler ve otonom sistemlerle donatılmıştır. Bu gelişmeler, daha derin ve karmaşık jeolojik yapılar altında bulunan kaynakların keşfine olanak tanımaktadır.

Açık deniz sondajları, petrol ve doğal gaz kaynaklarının keşfi açısından önemli bir alan oluşturmaktadır. Derin deniz sondajı, zorlu koşullarda gerçekleşen bir süreç olup, yeni teknolojiler ve yöntemlerle giderek daha güvenli ve verimli hale gelmektedir.

Gelecekte yapay zeka, makine öğrenimi ve diğer dijital teknolojilerin entegrasyonu, sondaj süreçlerinin daha etkili ve çevre dostu olmasını sağlayacaktır. Yenilenebilir enerji kaynaklarına yönelik sondaj uygulamaları, fosil yakıtlara olan bağımlılığı azaltma yönünde önemli adımlar atılmasına olanak tanıyacaktır.

Sonuç olarak, sondaj teknolojisi, hem enerji üretimi ve kullanımı, hem ekonomik büyüme hem de çevresel sürdürülebilirlik açısından oldukça büyük bir öneme sahiptir. Gelişen teknolojiler, çevresel etkilerin azaltılması ve doğal kaynakların verimli kullanımı için önemli fırsatlar sunmaktadır. Sondaj endüstrisinin, bu fırsatları değerlendirmesi ve çevresel sorumluluklarını yerine getirmesi, gelecekteki başarıları için kritik bir faktör olacaktır.

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CHAPTER V

Fracture Mechanics of Failure Analysis and Applications

Ferit ARTKIN[1]

Introduction

Fracture mechanics still seems to be a secondary issue in failure analysis, even though fatigue crack propagation and fracture are responsible for a large portion of failure events in industrial practice. Following a summary of the main issues in both failure analysis and fracture mechanics, scientists determine which failure analysis problems fracture mechanics can (and cannot) resolve. Its usefulness in failure analysis is determined by the accuracy of fracture mechanics, which is much more obvious from the design stage. In failure analysis, it would be helpful to have a better grasp of the application conditions as well as the limitations and requirements of fracture mechanics.

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The technique of fracture mechanics is used to identify and forecast failure of a component that has a crack or other flaw. A part's existence of a fracture increases the stress in the vicinity of the crack, which might lead to failure sooner than anticipated when utilizing conventional material strength techniques. The principles of material strength are used in the conventional method of part design and analysis. The stresses brought on by the imposed loading in this instance are computed. Depending on the failure criterion, failure occurs when the applied stress is greater than the material's strength (either yield strength or ultimate strength).

A stress intensity factor is determined in fracture mechanics by taking into account the component shape, crack size, and applied stress. When the material's fracture toughness is exceeded by the stress intensity factor, a fracture occurs. The crack then grows quickly and unsteadily until it cracks.

The Importance of Fracture Mechanics

There are numerous significant reasons why fracture mechanics is a topic worth considering:

- Cracks and crack-like flaws are far more common than one might think. Cracks could be already present in a section or could appear as a result of extreme stress or exhaustion.

- In general, a material's fracture toughness reduces as its strength increases. It is possible for many engineers to make mistakes due to their innate preference for stronger materials.

- Parts may fail at lower loads than anticipated when utilizing the material strength technique if fracture mechanics are ignored.

- Brittle fractures fail quickly and catastrophically, and there is little warning.

Figure 1. Fracture and Mechanics and Strength of Materials.

The tanker SS Schenectady, one of the Liberty Ships of World War II and one of its most famous wrecks, is seen in the picture below. She was moored at a handy pier at Swan Island in calm weather on January 16, 1943, just after returning from sea trials. The hull abruptly broke in two right aft of the superstructure, with a bang that was audible from at least a mile distant.

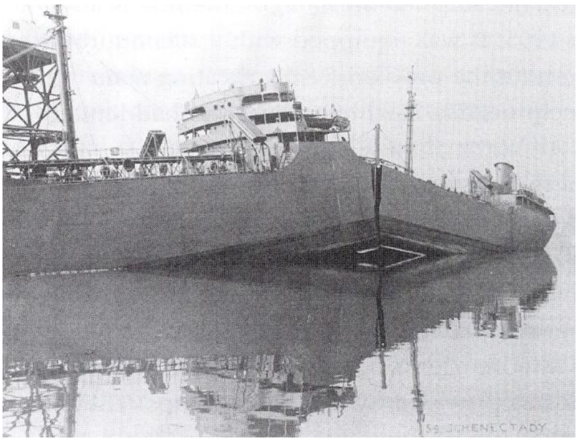

Figure 2. The SS Schenectady breaks in two while docked (Wikipedia, 2024).

Near the keel, the fissures extended from port and starboard, and the keel itself was broken, with the bow and stern curving upward out of the water and sinking to the river floor (Thompson, P., 2001).

The reason of the fracture was not entirely known at the time; the Board of Inquiry examined a number of possibilities, such as "locked" strains, abrupt climatic changes, or systemic design defects, while the Coast Guard's official report blamed the incident on a defective weld. The most frequent reason for these incidents was defective welding, particularly when subsequent investigations showed that several shipyards had used subpar working procedures. However, even in such cases, it was evident that fewer than half of all significant fractures were caused by this type of welding. Subsequent analysis revealed that a brittle fracture brought on by subpar steel was most likely the cause of failure. This would become extremely fragile in cold temperatures, aggravating pre-existing flaws and increasing the likelihood of fracture (Thompson, P., 2001) (Murray, C., 2015).

Concentrations of Stress Near Cracks

The tension in the component increases close to the crack's tip because cracks behave as stress risers. Consider the situation of an elliptical crack in the middle of an infinite plate as a straightforward example:

According to theory, the tension at the ellipse's tip is determined by:

$$\sigma_{max} = \sigma\left(1 + 2\sqrt{\frac{a}{\rho}}\right) \tag{1}$$

where σ is the nominal stress and ρ is the radius of curvature of the ellipse, $\rho = b^2/a$.

The theoretical stress becomes closer to infinity as the fracture tip's radius gets closer to zero. Physically impossible, this infinite tension is referred to as a stress singularity. Rather, the material experiences plastic deformation at a certain distance from the fracture tip as a result of the stress being dispersed across the surrounding material. The term "plastic zone" refers to this area of plastic deformation, which will be covered in more detail later. When the fracture point is blunted by plastic deformation, the radius of curvature rises and the stresses return to finite values (Figure 3.).

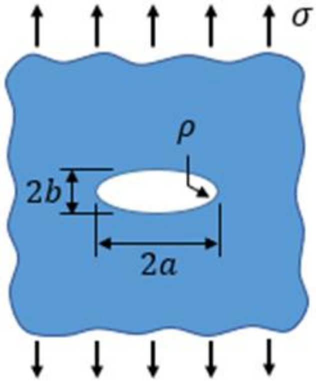

Figure 3. The concentration of tension surrounding a crack is shown schematically.

Alternative techniques have been developed to describe the stresses around the fracture tip due to the plastic zone that forms around the crack tip and the stress singularity issues that occur when the stress concentration approach is utilized. Today, the most popular approach is to compute a stress intensity factor, which is covered in more detail in a subsequent section.

Modes of Loading

The direction of a crack with regard to loading is defined by three fundamental modes. One or more modes may be used to load a crack. The three fundamental mechanisms of fracture loading are depicted in the image below. The fracture surfaces are separated by a tensile tension in mode I, also known as the opening mode. The shear mode, or mode II, is characterized by shear stress that causes the fracture surfaces to shift parallel to the principal crack size. The tearing mode, or mode III, is characterized by shear stress that causes the fracture surfaces to shift perpendicular to the size of the original crack.

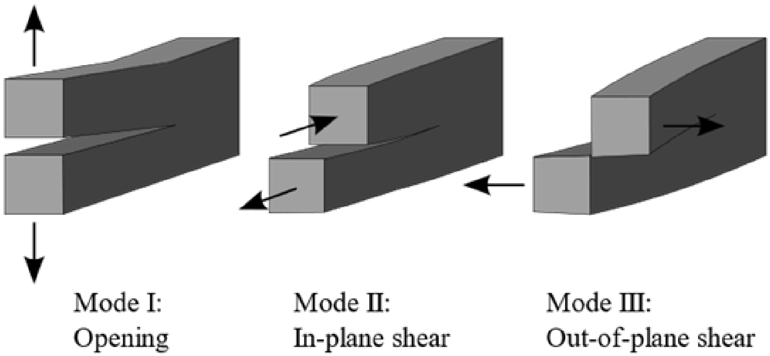

Figure 4. Schematic representation of the three basic modes of crack loading (Wikipedia).

As the worst scenario and most prevalent, Mode I is nearly often taken into account in engineering analysis. Cracks often develop in Mode I, however as the picture above illustrates, if a crack does not begin in Mode I, it will change into Mode I on its own.

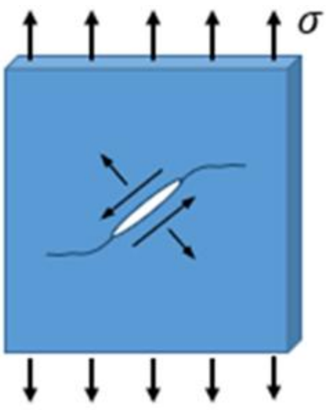

Figure 5. Tensile Forces on the Crack.

Fracture Toughness

A material may withstand applied stress intensity up to a critical value, after which it will fail and a fracture will form unsteadily. This essential stress intensity is the material's fracture toughness. The environmental composition (air, freshwater, saltwater, etc.), loading rate, material thickness, material processing, crack direction, and ambient temperature are some of the numerous variables that affect a material's fracture toughness. These considerations should be made when deciding on a fracture toughness value to use in design and analysis.

Fracture Toughness and Thickness

As material thickness grows, fracture toughness falls until the component is sufficiently thick to be in the plane-strain state. Fracture toughness is a constant number called the plane-strain fracture toughness above this plane-strain thickness. Of major relevance is plane-strain fracture toughness in Mode I loading, which is represented by the value K_{IC}.

$$K_c = K_{IC}\left[1 + B_k\, e^{-(A_k t/t_0)^2}\right] \qquad (2)$$

The plane strain thickness at critical loading, denoted by t0, is determined as follows: t represents the material thickness, while Ak and Bk are material constants

$$t_0 = 2.5\left(\frac{K_{IC}}{S_{ty}}\right)^2 \qquad (3)$$

where Sty is the material's tensile yield strength.

The thickness-specific fracture toughness calculation mentioned above was used to create the following graph for a sample material, 15-5PH, H1025. It is evident that this material's fracture toughness is 90 ksi*in $^{0.5}$ at lower thickness values and drops to plane strain toughness of 60 ksi*in $^{0.5}$ as thickness rises, after which it stays constant.

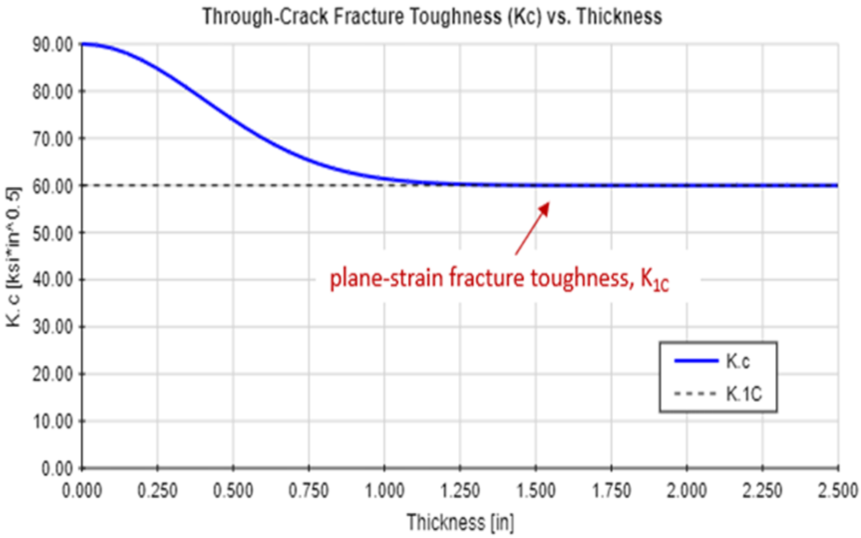

Figure 6. Fracture Toughness and Thickness Graph.

In design and analysis, it is still a good idea to utilize the plane strain fracture toughness value, even if fracture toughness may be roughly estimated as a function of component thickness.

Fracture Toughness and Strength

Fracture toughness typically reduces as strength increases for a particular class of materials. Heat treating a block of material to improve its strength characteristics will typically result in a decrease in the material's fracture toughness.

The fracture toughness and material strength for different material classes are displayed in the figure below. It is evident that the fracture toughness of many materials, particularly engineering metal alloys and engineering polymers, diminishes as strength increases.

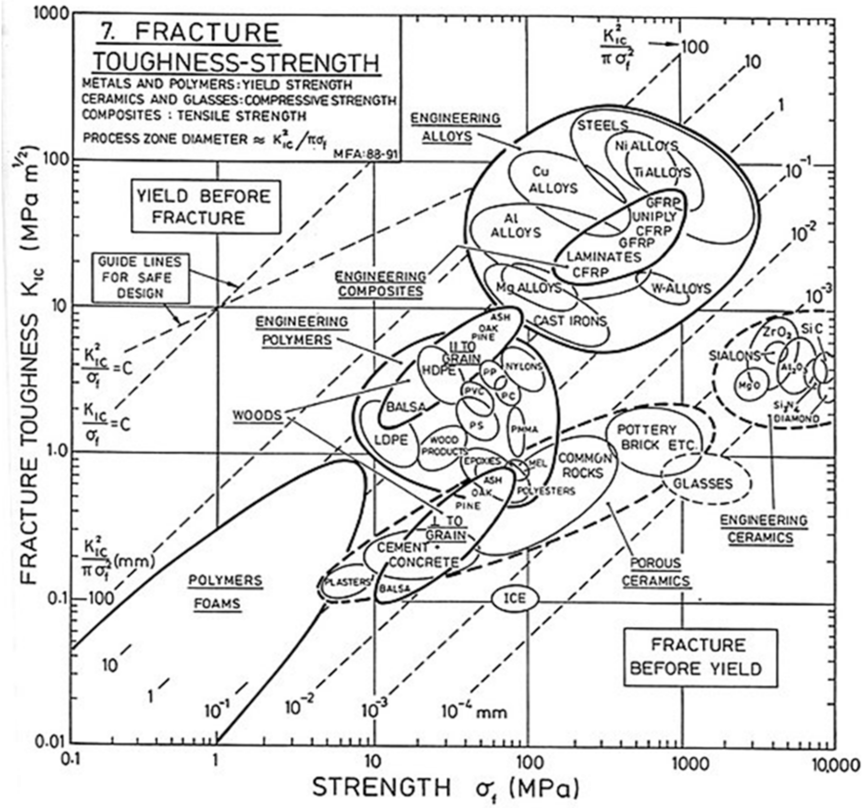

Figure 7. Fracture Toughness and Strength, (Wikipedia, 2024).

Fracture Toughness and Crack Orientation

Crack orientation in relation to grain direction usually affects a material's fracture toughness. Thus, crack orientation is usually given together with fracture toughness measurements.

The following graphic illustrates potential fracture orientation and grain orientation combinations for both rectangular and cylindrical geometries. The orientation of cracks is indicated by two-digit codes. Perpendicular to the crack face is the direction indicated by the first digit. The direction of the fracture path is indicated by the second number.

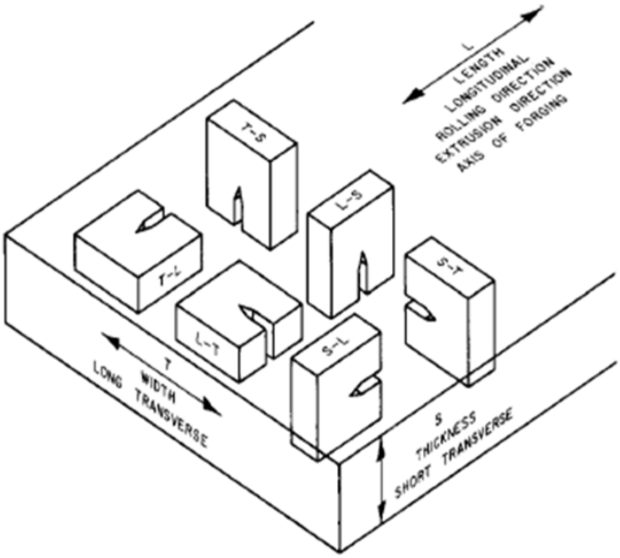

Figure 8. Fracture Toughness and Crack Direction I, (MIL-HDBK-5J).

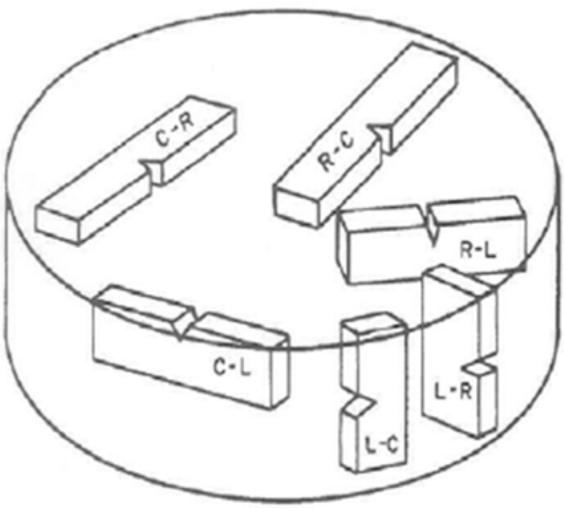

Figure 9. Fracture Toughness and Crack Direction II, (MIL-HDBK-5J).

Ductile and Brittle Fracture

The terms "brittle fracture" and "ductile fracture" are used in two different contexts. The fracture mode and fracture mechanism are these frameworks of reference.

Materials scientists typically refer to the fracture mechanism, which explains the fracture event at the microscopic level, when discussing brittle and ductile fracture. Cleavage is typically the brittle fracture mechanism, while dimpled fracture, commonly referred to as microvoid coalescence, is the ductile fracture mechanism. Brittle fracture is linked to the mechanism of cleavage. Very little plastic deformation occurs, and the fracture surface has ridges and seems smooth. Ductile fracture is linked to the microvoid coalescence process. The fracture surface appears dimpled like a golf ball due to this process, which involves the development, growth, and coalescence of tiny voids in the material that are triggered by plastic movement.

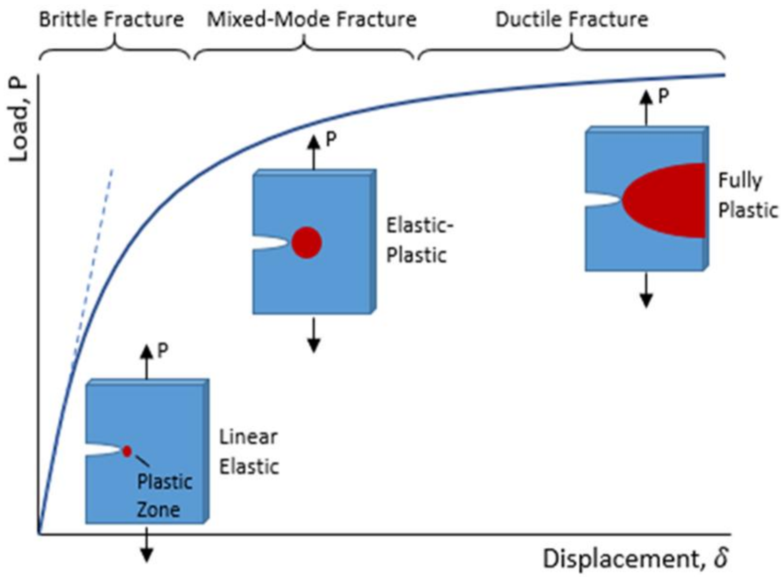

Figure 10. Fracture Toughness and Crack Direction II, (MIL-HDBK-5J).

The fracture mode, which characterizes the material's high-level behavior during the fracture event, is typically referred to by mechanical engineers when discussing brittle and ductile fracture. The fracture mode is seen in the image above.

The load-displacement curve is depicted with broken specimens at various points along it. Stresses in the component are less than the material's yield strength in the linear section of the curve with the lower applied load. If the part breaks in this location, it is referred to be a brittle fracture because it fails earlier than expected using material strength measures. Note that in this location, the plastic zone (shown in red) surrounding the fracture tip is generally tiny, thus the linear elastic assumption is true, and Linear Elastic Fracture Mechanics (LEFM) may be utilized to evaluate the component. The plastic zone size grows in proportion to the load. Ductile fracture occurs when a component fails in the upper portion of the load-displacement curve.

If the plastic zone size exceeds the application of LEFM but has not yet extended throughout the cross-section, elastic-plastic techniques such as the Failure Assessment Diagram (FAD) can be employed to examine the part. Once the plastic zone size has expanded over the whole cross-section (gross cross-section yields), fracture mechanics methods are no longer applicable, and the cross-section must be studied using the material strength approach.

Failure Assessment Diagram (FAD)

If LEFM is not applicable, elastic-plastic analysis should be employed to account for plasticity effects around the fracture. The Failure Assessment Diagram (FAD) is the most used elastic-plastic analysis approach.

Note that in the picture below, the failure locus for LEFM is shown by a dotted horizontal line, whereas the FAD failure locus is located below the LEFM. This suggests that the failure forecasts provided by LEFM are insufficient. The decreased failure locus on the FAD curve is due to plasticity around the crack tip, which increases the effective crack length and consequently the severity of the crack condition.

Also, the failure locus for plastic collapse (i.e., the failure locus anticipated using material strength techniques) is represented by a vertical dotted line. The FAD failure locus crosses across the plastic collapse locus and pushes it to the right, suggesting that the component is becoming stronger. This significant increase in strength is due to strain hardening.

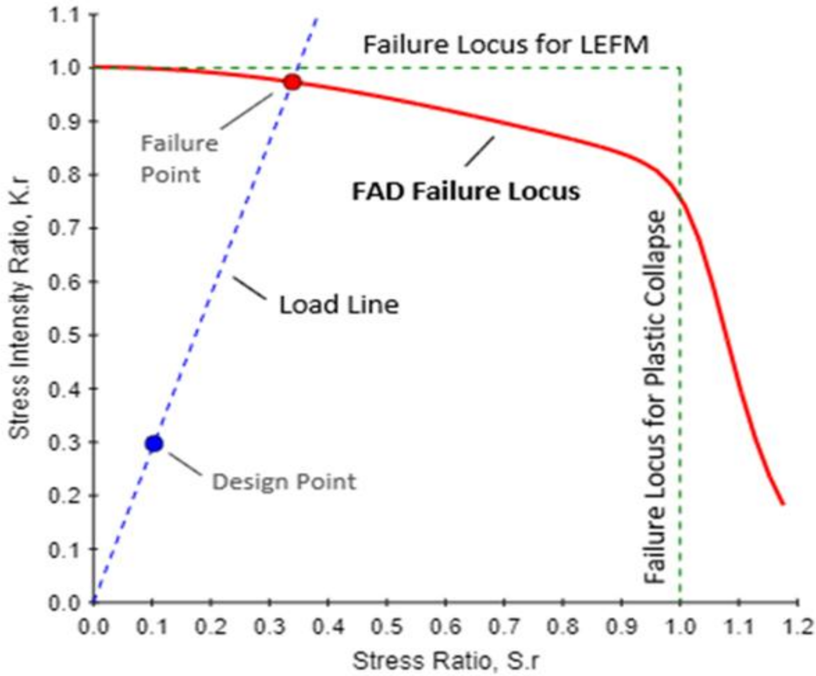

Figure 11. Fracture Toughness and Crack Direction II, (MIL-HDBK-5J).

The FAD approach's ability to account for material plasticity while employing linear elastic stress intensities is its last noteworthy feature. This offers the FAD method's simplicity and is a significant benefit over alternative elastic-plastic techniques.

Residual Strength Curve

The residual strength curve displays the part's strength in relation to the size of the crack. The part's strength and the material's yield strength are equivalent in the absence of a crack. Nevertheless, strength (i.e., the amount of stress that can be tolerated before collapse) declines as the fracture widens.

The residual strength curve is displayed in the example scenario in the following figure. The material used in this instance has a yield strength of 145 ksi and a plane strain fracture toughness of 60 ksi*in$^{0.5}$. The plate is 2 inches broad and has a crack down the middle. In red is the residual strength curve. Above this curve, failure will occur for any stress value for a given fracture size.

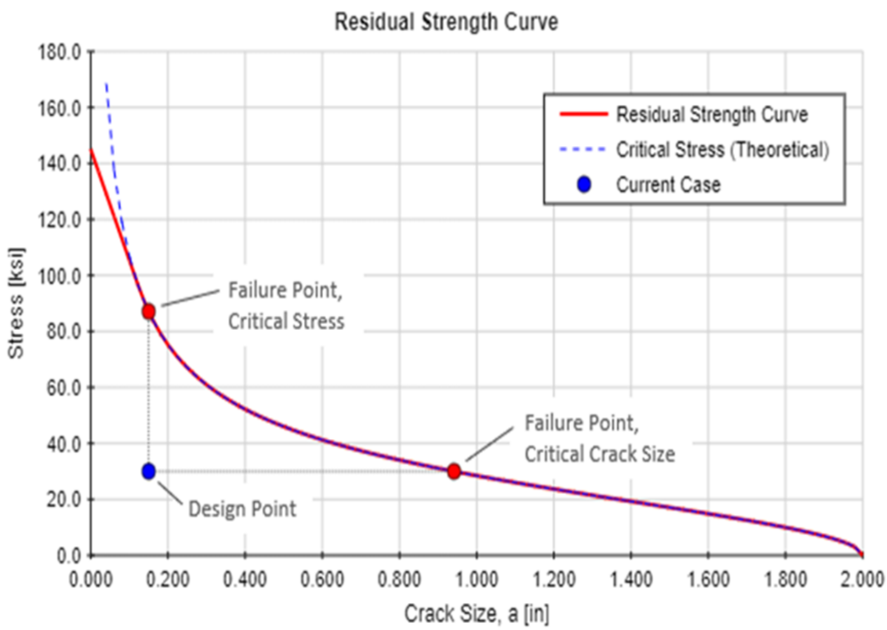

Figure 12. Residual Strength Graph.

Take note of the blue dotted line in the graph above, which represents the theoretical critical stress curve. This theoretical curve may be characterized as follows: It gives the theoretical critical stress value as a function of fracture length.

$$\sigma_{crit} = \frac{K_{IC}}{Y\sqrt{\pi a}} \tag{4}$$

The fact that the geometry factor Y depends on the fracture size is often significant. As the fracture size varies, the Y value will also fluctuate. At the part boundary, the residual strength curve falls to the critical stress value of 0, which is explained by the fact that the Y value will typically peak as the crack size rises in relation to the part dimensions.

When the fracture size becomes closer to zero, it's also crucial to remember that the theoretical critical stress gets closer to infinite. Since the material's tensile strength establishes an upper limit on the amount of stress it can tolerate, this is obviously impractical. A straight line is formed between the material's tensile yield strength and the tangent point on the theoretical critical stress curve in order to smooth out the residual strength curve in the tiny fracture area. In certain situations, determining the tangent point is impossible. In this instance, Liu advises that the point at which the theoretical critical stress equals two-thirds of the material's tensile yield strength might be interpreted as the transition point between the straight line curve and the theoretical critical stress curve.

Conclusion

For the analysis and prevention of equipment and structural component failures brought on by the formation and spread of fractures, fracture mechanics is the finest technique currently available.

The study of fractured components under static load circumstances—that is, settings with constant loads that do not fluctuate over time—has been covered in this material on fracture mechanics. The stress level at the crack tip will fluctuate in the event that the load varies over time. If the change in stress intensity is greater than the material's threshold stress intensity, a fracture will develop. Fatigue crack growth is the development of a crack under situations of fluctuating stress intensity. It is crucial to remember that the geometry factor Y generally depends on the size of the fracture. As a result, the Y value will fluctuate along with the fracture size.

The behavior of materials with defects may be understood and predicted with the help of fracture mechanics. Engineers are able to build and operate structures and components more safely and effectively by using the concepts of fracture mechanics. Fracture mechanics should be used in conjunction with other engineering tools and approaches, but it's crucial to understand its limits.

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