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INDUCED STRESSES & DISPLACEMENTS CAUSED BY SINKHOLE DEVELOPMENT

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Highlights

- Analyzes of induced stresses and displacements in underground cavities.
- Examining the impact of groundwater on rock mass stability and sinkhole risk.
- Understanding the mechanics of progressive rock failures in overburden layers.
- Providing engineering implications for sinkhole mitigation in subsurface environments.

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ABSTRACT: Induced stress-strain conditions around underground spaces which could be excavated or naturally formed have their destructive influences on the surrounding rock masses. Roof and sidewall rocks surrounding these spaces are strained due to 3D induced stress fields formed just after their introductions. Cavities/excavated underground spaces have their stability difficulties due to surrounding rock masses' strength/discontinuity features. Stable rocks around these spaces including stable pillars are candidates which supply deformations in time due to their long-term strength characteristics. Collapsing of the rock masses surrounding the underground spaces causes caving effects through the rock masses above the spaces. If the collapsed rock masses cannot support the above overburden dead-loads as fragmented rock fills in the caved spaces, progressive failures are continued upward directions to form further subsidence deformations. Underground water circulations at the caved spaces provide different circumstances including the transportations and/or solution of the caved rocks in time. These processes eventually provide progressive subsidence/sinkhole in time due to elimination of submerged caved/fragmented rocks. The procedures causing progressive roof failures were analysed here for hypothetical rock mass conditions to understand the procedures' governing factors. Evaluating these factors supply hints about what could be the engineering manners to decrease the risk of sinkhole developments.

Keywords: *Ground Displacements, Sinkholes, Subsidence, Ground Surface Deformations, Underground Spaces*

1. INTRODUCTION

Earth has numerous solid, liquid and gas form elements and it has a crust cover consisting of different types of rock masses. Rocks with their mineral contents and structural configurations have their mechanical properties which are differentiated through their water contents (saturations), void ratios, discontinuity contents, etc. Uncertainties in the determination of representative values for these properties have supplied their complexities in engineering decision circumstances. Since the values characterising the strength or mechanical behaviours of the earth crust materials/masses, which are mainly rocks, cannot be provided through referenced value intervals. Field and laboratory tests performed to characterise rock/soil materials or masses should be repeated through test specimens which should be sampled in regular intervals to reach meaningful averaged values for the selected rock mass locations (in/on the earth crust). Actually, all these efforts cannot eliminate influences of uncertain factors influencing the mechanical behaviours of the rocks/soils. Rock engineering context has the basic explanations related to these uncertainties and International Society of Rock Mechanics, ISRM, has gradually suggested rock testing methods for rock materials/masses to help engineers via the standardisations. Similar complex decision environments are encountered by engineers to supply decisions for the different aspects related to the rock mass cavities. The rock masses can be massive and uniform in their characteristic structures (it is very rare to come across such rocks), but even these intact rocks have their porosities influencing their mechanical behaviours besides their permeability values. Liquids and gasses occupying the rocks' pore volumes have their effects on the rock masses' mechanical properties. Saturated rock masses can be influenced through pressurised groundwater, oil, and natural gasses at shallow/deep rock reservoirs conditions. Pressurised medium (water, oil, and gas types) in

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rock porosities have their relations with induced stresses-strains around the pores, cavities. Possibilities of any change in pore pressure in rock masses then have their stress-strain redistributions around the pores. Pumping out the groundwater, oil and natural gasses for different purposes then result in changes at rock pore pressures. Thus, change in pore dimensions due to overstressed peripheries of pores are then expected results at oil, natural gas fields, and groundwater dicharging pump locations. In addition, earthquake vibrations, subsidence due to man-made cavities, man-made vibrations (machine or blast originated ones), etc. are the other external influences on pore pressure-oriented rock mass deformations. When the voids or cavities are in concern, the rock masses' reservoir dimensions, porosities & permeability properties of the rock masses direct the available open space volumes in the rock masses. Encapsulating with impermeable rock masses, certain rock masses have their potential to have liquids, gasses, or liquids+gasses in their micro-cavities. Underground water, oil, and gas reservoirs have their individual characteristics but at the beginning the conditions started through proper reservoir bedrocks which have huge amounts of void spaces in it.

Natural voids, cavities have surrounding rock masses which have their tendency to resource fractures, and their propagations. These fractures (discontinuities) either belong to the surrounding rock masses or they are initiated due to these rock pores, voids, which are controlled by induced stress and pore pressure relations (conditions). In addition, surrounding rock masses' mechanical properties are also governing factors in rock fracturing procedures. When the rock pores, voids, turn into small cavities and then to the caves, and cave-network, it is important to concentrate the types of host rock masses which are most probably karstic rock types.

Rock masses mechanical behaviours, especially at the roof layers of rock voids, cavities or caves are important for the cases of vertical upward enhancement of these underground spaces. These layers either inherit their upward extensions (caving) due to their higher strength characteristics (Fig.1a) or they supply pathways to these extensions due to their fractures and weakness zone directions. Fissures, joints and sets of discontinuities, even the fault zones, are the common instability causes directing the collapses of overburden rock masses (layers) into the existing underground spaces. Actually, collapsed rock masses always have higher volumes, (due to fragmentation), when their original volumes are taken as reference values. Thus, caved rock masses into the existing underground spaces eventually filled all the empty spaces created during the caving evolvements (Fig.1b). Caved roof rock zones have more open spaces among their blocked & fragmented rocks. These caved rocks have then possibly been compacted firmly by induced 3D stresses. It is very rare to visualise such situation but the shallow coal seam which had been mined with underground mining methods and were then excavated with open pit mining operations to mine-out the remaining coals left as coal pillars of abandoned coal mine supplied such opportunity, (Fig. 1), [1, 2, and 3]. Caves are like other underground spaces have their instability circumstances and they progressively approach their collapsing phases due to the induced fractures initiated&propagated in their surrounding rock masses. Fractures elongating at the middle of the roof strata of the caves, galleries, etc. are examples of induced stress fracturing (Fig. 1c). In some occasions, fracturing and caving processes of the caves' roof rocks have reached to the ground surface to form sinkhole type failures (Fig, 1d). Failure of roof rocks above caves could be slow and in progressive manner or it can also be sudden events like especially for their caprock collapses. It can also be expected to be a combined-event which consists of these two caving behaviours in the same sinkhole development. The procedures are depended on the type of rock masses surrounding the underground spaces which initiate roof rock caving steps.

Caving of the overburden rock masses have purposely been engineered in certain mining method steps, (procedures), to handle safety of works & workplaces. For instance, low grade ore reserves are forced to be caved in controlled manner towards the underlying ore collection shuts for their loading and hauling operations (sublevel caving method, and block caving method). Rock masses over the ore bodies in these operations are also caved. These mining methods form large scale crater-like ground surface subsidence features in time. In some coal mining operations, mine-out panels of the coal seams cannot be kept open. Thus, they are forced to be collapsed like the case at underground long-wall mining method applications. This is necessary to protect the underground coal mines from "*coal-gas explosions*", and "*coal mine fire*" dangers. In these caving operations underground mine spaces' volume which are forced to be collapsed are the main governing factors directing caving advancing upward over these spaces. Types and mechanical properties of the overburden rock masses in these cases are also important factors on subsidence influences. Sublevel caving and block caving mining methods on the other hand have their orebody caving actions in their main mining procedures. Mechanical properties of overburden rock masses and their discontinuity contents govern the caving procedures advancing upwards towards the ground surface. In some cases, underground spaces supply progressive roof rock failures due to induced 3D stress concentrations. In these circumstances, dimensions of underground empty spaces are getting changed with extra progressive roof collapses. Then vertical chimney type underground spaces could possibly be formed. When these roof failures are approached to the ground surface, caprock parts of the overburden layers then collapse to form sinkhole type features, [6].

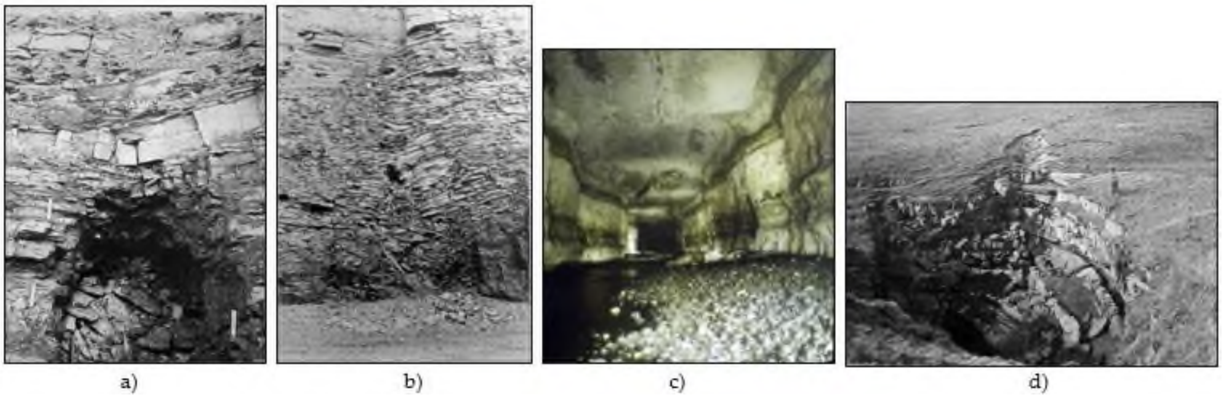


Figure 1. a) Roof collapse at an abandoned coal gallery inherited with thick overlying strata [2 & 3], b) Abandoned coal mine galley which had been totally filled with caved overburden roof rocks [2 & 3]; c) Fracturing roof strata at Sof-Omar cave (Ethiopia), [4], d) Sinkhole formed at Yorkshire (England) due to collapse of roof layers at a limestone cave, [5].

2. UNDERGROUND SPACES AND THEIR ROOF FAILURES

There are different types of volumetric spaces used by human civilisations since the beginning of human history. Surface structures have been supplied by different types of volumetric living, working and other civil purpose spaces on the earth crust. Underground structures on the other hand provide structures at subterranean spaces. Actually, caves as underground spaces had been the earlier urbanisation locations before man-made underground excavations, and surface structures. There are many types of underground spaces in rock masses which are naturally formed or excavated. They are used for different human requirements. T*he Commission of Artificial Cavities of the Italian Speleological Society*" supplied classification for this complex usage of underground spaces. Galeazzi, [7], wrote about this classification which include 7 main branches: a) Hydraulic underground works, *(1.Water level control, drainage-ways; 2.Underground stream interception structures; 3.Underground water ducts, aqueducts; 4.Cisterns, water reservoirs; 5.Wells; 6.Hydraulic distribution works; 7.Sewer; 8.Ship, boat canals; 9.Ice wells, snow-houses, 10.Tunnels or ducks with unknown function),* b) Hypogean Civilian dwellings, *(1.Permanent dwellings; 2.Temporary shelters; 3.Underground plants, factories; 4.Warehouses stores, cellars; 5.Underground silos; 6.Stables for any kind of animals; 7.Pigeon houses; 8.Any other kind of civilian settlements),* c) Religious cult, *(1.Nymphaeum, Mithraea temples, sacred wells, shrines, monasteries, churches, and chapels, etc. 2.Burial places),* d) Military & war works, *(1.Defensive works, 2.Galleries and connecting passages, 3.Mine and countermine tunnels, 4.Firing stations, 5.Deposits, 6.Sheltered accommodation and soldiers, 7.War shelters for civilians),* e) Mining works, *(1.Aggregate quarries, 2.Metal mines, 3.Mines and quarries of other materials, (non-metallic), 4.Non-specific mining surveys, 5.Underground spaces to grow vegetables),* f) Transit underground works, *(1.Tunnels for vehicles, pedestrians or horses, 2.Transit works, not military, 3.Railway tunnels, tramways or funicular (out of use), 4.Non-hydraulic wells, shafts etc.)*, g) Other works. Underground spaces naturally exist as micro voids, pores, (porosity properties of rock masses), cavities (formed due to rock forming circumstances, and enlargements of micro voids through chemical weathering, and further fracturing & crushing), caves, and cave networks in karstic rock masses are all have their instability problems which have tendency to form ground surface vertical deformations as subsidence or sinkholes. At this point, it should be noted also the vertical deformations of a large-scale surface area due to pumping out of groundwater, oil, and natural gasses through underground voids.

If there is a space in the earth crust, there are induced stresses around them. Therefore, if the surrounding rock masses cannot bear these 3D stresses, they are deformed and supply new fractures or they provide fracture propagations for their existing fracture networks. Thus, due to gravity, tectonic stresses, and earthquake vibrations underground spaces which have instable roof and siderocks have eventually collapsed. Existing spaces in earth crust are also potential candidates for further collapsing events. Actually, when the induced stress distributions around underground spaces are considered by evaluating available research: rock-load height calculation criteria and dead-load concerns are common explanations. Due to the complexity of the earth crust content, rocks cannot be considered massive material. They are inhomogeneous and they have different mechanical characters in different parts of their mass bodies. Induced stresses influencing vertical and horizontal peripeheries of the underground spaces cannot be transferred through these empty spaces without available load-bearing solid pillars. Therefore, these stresses are redistributed around the spaces by supplying bridge type load transfer features over empty spaces. Rock-load height concept (rock mass classification procedure) supplied by Terzaghi, (Fig 2a), [8], is then based on the estimation of this height which is different for different rock mass characteristics. Basically, massive rocks have lower rock-load height with respect to the rock masses having discontinuities [8]. When the rock-load height is getting higher consequently dead-loads calculated for certain sections of the underground spaces (roof area= roof span x length of the selected section of the space) are getting higher. Shape and dimension of the spaces (which have direct influences on the spaces' roof spans) are then the important design features besides several other factors like surrounding rock mass mechanical behaviours for stable man-made underground openings in mining and civil engineering context. Kirsch, [9], for instance, supply estimation for the induced tangential and radial stresses formed around a circular opening in a homogeneous & uniform medium which is loaded under a 2D stress field. Consideration of rock masses as homogeneous and uniform (massive) in condition is hypothetical but, applying Kirsch solutions for circular underground spaces supply also valuable information for further rock mechanics analysis. In this content, work supplied by Li et al. [10] covered information how the shape and positioning of the selected underground space are also influencing factors on induced stresses, (Fig. 2b and 2c). They presented induced tangential stress concentrations around elliptical holes which were considered that they were under uniaxial compressions and they had different inclination angles.

It is obvious that vertical stresses above the underground spaces are bridging around the empty spaces which consequently increase the tangential induced stresses according to the spaces' span values. Same shape and size of the underground spaces illustrated in Fig. 2b and 2c cause different induced tangential stresses which were calculated by Li et al. [10] as 5P for horizontally positioned elliptical holes, and 2P for vertically positioned elliptical holes. Vertical eliphtical holes have more advantage in stability circumstances with respect to the horizontally positioned elliptical holes. Actually, existing stable caves, natural conduits, and cavities have their clues of their stability characteristics, (Fig. 3), like; Arch shaped roofs, inclined and nearly vertical elliptical conduit cross-sections, reinforced roof and sidewall rocks at caves, (including their fractured inner bodies and caves' inner peripheries), with precipitated carbonates, pillar type roof supports at caves through developed stalactite & stalagmite, relatively good strength quality rock masses surrounding the caves, comparatively small size cave with no nearby openings, and relatively low induced stress locations in the rock masses, etc. These are the common features of stable caves & cavities around the world. Caves which had not gotten opportunities to have these kinds of shapes, dimensions, field stresses & induced stresses, rock strengths, earth crust positioning conditions had gradually collapsed. Their overburden rocks had been gradually caved into their empty spaces. Some of them have delivered examples of ground subsidence, sinkholes, or deep valleys according to their caving procedures in geological times.

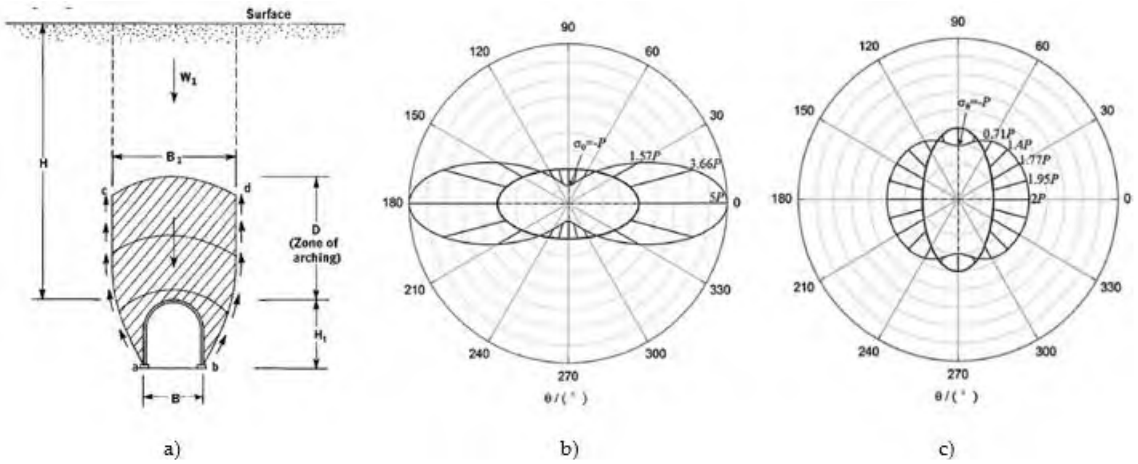


Figure 2. a) Rock-load height concept supplied by Terzaghi, [8], b) Induced tangential stresses around elliptical (long axis length=12mm, short axis length=10mm) holes with (b) horizontal (0^{o}) and, (c) vertical (90^{o}) inclination angle under uniaxial compression (P), [10].

3. UNDERGROUND SPACE COLLAPSE AND SUBSIDENCE

Since the natural underground spaces in earth crust in micro and macro scale are one of the reasons why the humans can manage to continue their civilisations. Man-made underground spaces for mineral, groundwater, and energy gaining purposes through engineering procedures have left underground spaces at the back in micro and macro scales. These spaces have a tendency to collapse to start rock mass caving events. Earth crust has many examples of underground space collapses & related overburden rock mass cavings explored and recorded by the researchers. The rock mass caving conditions illustrated in Fig. 1, and basic subsidence features & results illustrated in Fig.3 and Fig.4 provide the cases illustrate the influences of rock masses' mechanical characteristic on the ongoing procedures of the downward deformations, (caving), of the rock masses. Caving which has been progressed (slowly or quickly) in the overburden rock masses depends on their mechanical properties and behaviours. Mining activities performed in history have abandoned numerous open underground spaces which have their potential for their caving activities in time to form subsidence or sinkhole type failures. Types of overburden rock masses affect the angle of influence zones. Fracturing and bending of the horizontal rock layers, homogeneous deformations through other rock types, etc, have influenced the downward movements of them through their fracturing & fragmentation procedures. If the abandoned underground mine openings are located in shallow depth ranges, their collapses form egg-voile types surface morphology (with many holes of depressions, Fig. 4a). Similarly, abandoned underground spaces have gradually formed stability risk for the surface urban structures. The situation presented by Pellicani, et al. [15] in Fig. 4b illustrates the surface areas which have higher failure risks due to abandoned underground spaces. Mining history includes excavation of coal and building stones through shallow underground mines which were mainly handled with room & pillar mining methods. Their abandoned rooms are the main sources of subsidence which influences the current urban and agricultural lands. These spaces have been analysed to predict their risks on the surface/underground structures, (Fig. 4c). Subsidence over coal mines had dramatic influences in urban areas. Therefore, countries which have abandoned coal mines have also their individual experiences of subsidence, and sinkholes. Singh & Dhar, [17], worked on subsidence types over coal mines, and they illustrated chimney type (steep-sided, Fig. 5c) subsidence migration, (there are also shallow-sided sinkholes which have volumetric upside-down conical geometries at their ground surface intersections over their steep-sided sinkhole layers). When the caving started in the overlying rock strata of coal rooms; these authors wrote that, "*caving migrates through the overlying strata until the fracture zone intercepts the unconsolidated overburden*", (Fig. 5a). The weak rock layers over the underground rooms, (spaces), collapse due to their tensile and shear behaviours, [18]. Caving of the roof layers migrates towards the ground surface by the effects of induced stresses and it can only be decelerated by rock strata which have higher strength values or "*bulking of roof debris*", [17], (Fig 5b). Subsidence influences over coal seam mining operation have studied by several researchers and their works have been handled through the subsidence and sinkhole risk evaluation literature related to underground mines and natural cavities. Heritage, [19] for instance presented numerical analyses results provided through FLAC 2D analyses to be used in the evaluations of subsidence over coal seam panels. Researchers in this field analysed; the mode of failures, vertical displacements, cumulative & incremental subsidence, rock failure modes, hydraulic conductivity differentiations for overburden rock masses through their 2D modelling procedures. Figure 6 illustrates one of the results related to rock mass hydraulic conductivity differentiation over the extracted coal panels of the coal field at Southern Coalfields of NSW, Australia, [19]. The rock masses' fracturing & their migrations over the coal seam resembles with the hydraulic conductivity increases. Heritage, [19], wrote that the vertical conductivity model here supplied output, (Fig. 6), which has "*a distinct high conductivity zone in the 60m above the seam*".

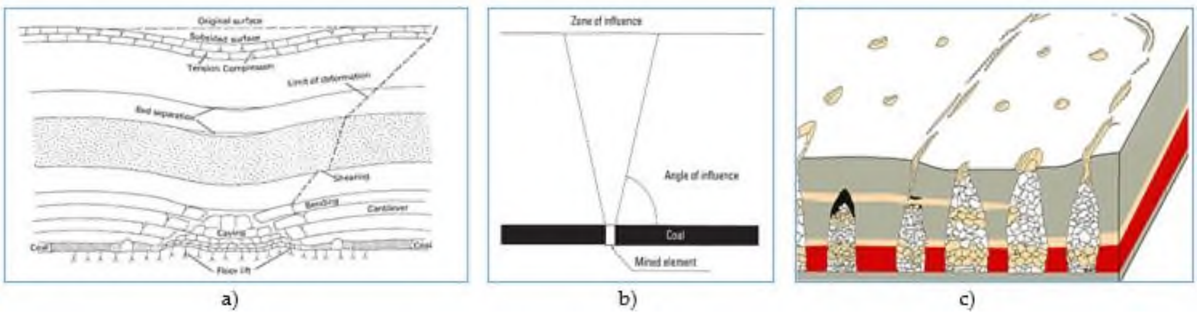


Figure 3. Subsidence influences, a) Deformations (caving) of overburden rock masses due to coal seam mining [11, modified from 12], b) Influence zone above coal seam galleries (or panels) which have tendency of caving (schematic illustration), [13], c) Collapses of over layer rock masses governed by induced stress conditions and rock mass discontinuities, [14].

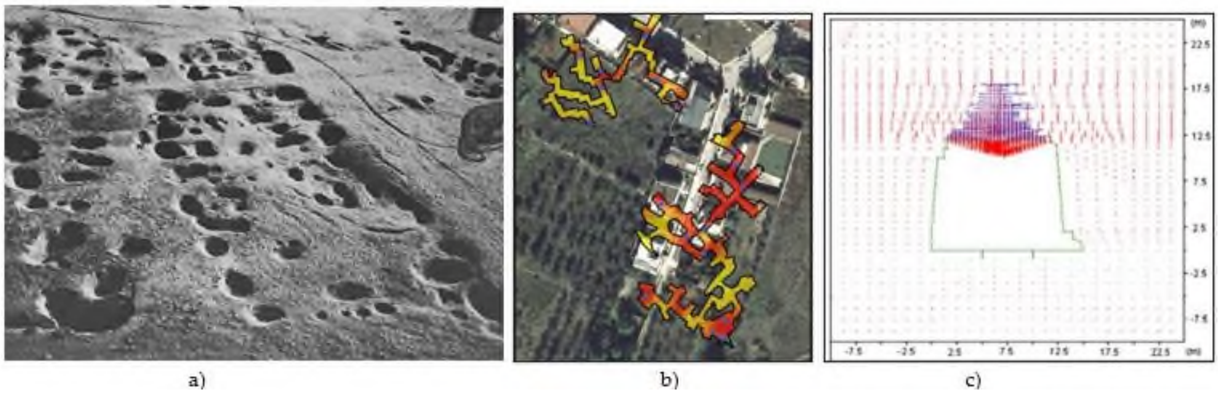


Figure 4. a) Ground surface deformations due to coal mine subsidence holes, troughs, and cracks above a coal mine at the Western Powder River Basin, Wyoming, US, (Photo-graph; C.R. Dunrud), [11], b) Location of instability evidences, (Barcelona Street, Altamura, Italy), [15], c) Example of numerical (distinct element method) analysis which helps to understand failure conditions around the underground mined out spaces at Castellana, Italy, [16].

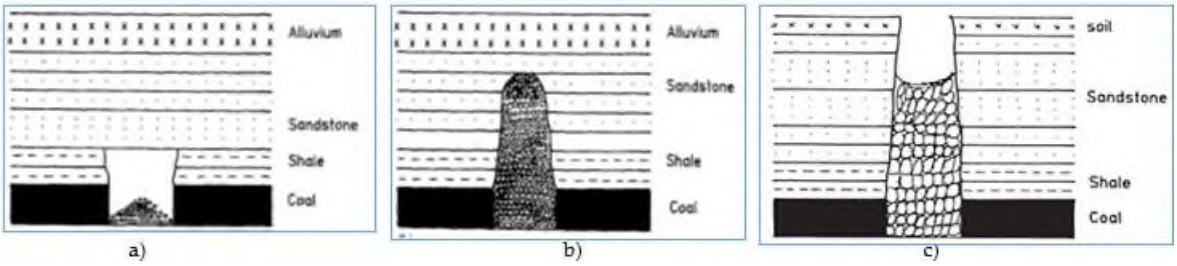
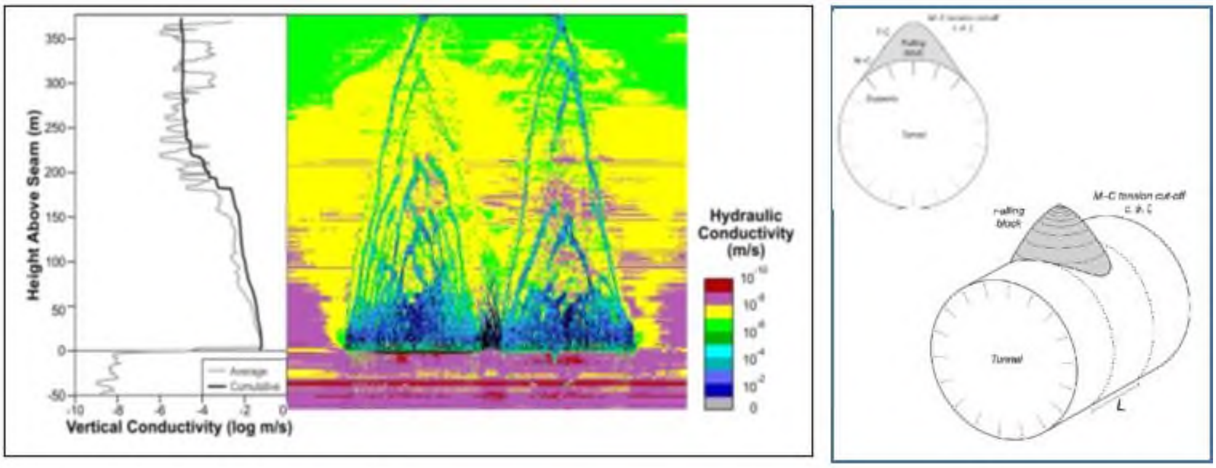


Figure 5. Rock mass collapse migration through overburden layers, [17].

Numerical model studies have obstrucals about their material behaviour models, approaches, *(rock mass behaviours, for instance, have not totally modelled, there are only criteria to evaluate these behaviours).* Uncertainties in input data form also unclearness for 3D rock mass property distributions. These natural features of rock masses cannot be eliminated but available approaches for rock mass mechanical behaviours, and developments in rock engineering research area push the numerical analyses to supply more reliable outputs for real-world rock engineering problems. However, Zhou, et al., [20] studied hard rock failures around underground spaces and they presented the complexity of the parameters in their failure analyses. Uncertainties in rock properties and their distributions in the rock masses have formed main unclearness in the results of the analyses in which engineers must supply a bunch of decisions to direct their engineering related works in the underground space operations (which covers dangerous conditions for work & work-place safety concerns). Thus, different approaches have then been handled to deal with these uncertainties including statistical analyses and/or expert decision support systems. The results supplied through them, (like rock failure criteria, rock mass classification systems, etc.) are valuable sources of engineering resources to be evaluated in engineering decisions. For instance, when the failures of roof layers of underground spaces are in consideration, (where there is a tendency of caving procedures), the work supplied by Park, [21], for hard-soils & soft-rocks (Fig. 8) can also be considered to understand mechanical failure mechanism of the "early phases of cavity formation" at the roof layers of underground spaces, (conduits, tunnels, etc.). Modelling rock masses above collapsed mine openings or natural cavities provides assistance during the evaluation of their influences and risks of failures. These considerations are valuable assets in our populated world which subsidence & sinkholes could possibly cause unprecedented damages to urban, industrial, agricultural land parcels. Therefore, evaluations & predictions of failure risks due to subsidence&sinkholes for these parcels are important. These works then should be realised by national and local governments to supply stable land parcels for different human activities. Numerical models therefore have their values especially in rock mechanic analyses to supply induced stress-strain cases for such subsidence influenced local areas. Numerical analyses performed for homogeneous massive metals which have uniform mechanical behaviours could supply more reliable results when compared with the heterogeneous solid materials. Rock masses have their numerous types and compositions with indefinite numbers of discontinuity contents. That means uncertainty of measured test data (laboratory or field data sets) cannot be put aside when the rock mechanics are under analyses & evaluations for their characteristics. When the decisions required to be supplied for the sinkhole risks for a specific land parcel, overburden rock masses above any underground spaces (natural or man-made excavations) should be analysed for their caving (subsidence) characteristics. However, contents covered undefined 3D rock characteristics and behaviours are comprehensive and complex in characteristics. Therefore, they are preferred to be considered with expertises like the cases of "rock mass classification rating systems". Shiau et al., [22], for instance supply idealised sinkhole analyses for their supplied course procedures. These authors assumed that the cross-sectional shape of the sinkhole cavity is round at the beginning. Then it can be enlarged to have conical cross-sectional shape, (when it is advancing towards the ground surface). The whole volumetric geometry of the sinkhole can also be defined like the cases described for Fig. 5 cases. The results obtained by Shiau et al., [22], through their idealised numerical models including limitations



a) b)

Figure 6. a) Rock masses hydraulic conductivity differentiation in modelled coal-seam overburden rock mass, [19], b) Triangular arch-shaped cavity considerations through Mohr-Coulomb (M-C) envelope & Tension-cut off (T-C), [21].

in, "the depth ratio (h/w), the width ratio (l/w), the soil strength ratio (c/γw), and the angle of internal friction (φ)", (Fig.7). When the caving procedures of sinkholes & subsidence, especially the chimney types of cavings are under considerations, the studies provided through field sinkhole observations, and numerical solutions offered for their failure considerations. These information and knowledge have been reviewed here to deliver reasonable explanations for the sinkholes and their induced stresses&strains at Karapinar (Konya, Turkey). Like the overlaying materials considered in Park analyses, [21], which were hard-soil / soft-rock, overburden rock masses above the sinkhole are layered low strength rocks. Sinkholes located in this region have their long-known history. As Dogan & Yilmaz, [23], stated that pumping (discharge) of groundwater for increased requirements of irrigation have decreased the groundwater level in the region. Gutierrez, [24], stated that the developments of sinkholes in this region have been related to the, "*Late-Quaternary lacustrine deposits of the Konya pluvial lake underlain by Pliocene limestone*". Dogan & Yilmaz also wrote that the lacustrine formation related to sinkholes near Konya was "Insuyu-formation" and it had been formed "*as a result of an extension regime during the Upper Miocene–Pliocene", [25]*". The types of rock masses in Insuyu-formation were listed as; "*thick limestone in the upper section, limestone, marl, clay, tuff and silt intercalation in the lower section",* [26, 27]. After supplied this information, Dogan&Yilmaz, [24], mentioned also about "*the thickness of fractured lacustrine limestone, suitable for karstification*". It has a thickness over 200m, [28]. Central region of Turkey is an elevated Plato, (850-1000m) and it is a hydro geologically closed region. Therefore, it has its own groundwater circulation circumstances, [24]. Main groundwater flowing direction towards the lowest ground surface area at the elevation of 902m at "Tuzgolu" Salt Lake, (Konya, Turkey). Groundwater paths and their numerous branches in the rock masses are then expected to form water circulation conduits which have formed micro & macro cavities (karstification). When these underground water circulation paths have come across weakness zones, these conduits may have interrupted with roof collapses. Rock materials solubility and fragmentation properties have then been governing factors in material removal away from the collapsed underground spaces' locations. Collapsed parts of the underground conduit spaces which have groundwater or not are then form additional small scale underground cavities at the roof of these conduits. As the induced stress with/without groundwater influences continue to affect stabilities of these conduits and cavities, it is natural to expect further roof & sidewall collapses as the strength of the surrounding rock masses have been overwhelmed by these influences. Thus, even the small-scale cavity which might be formed at the roof of the underground conduits are important factors to initiate sinkhole type caving actions at the overburden rock masses. If the surrounding rock masses of underground spaces are weaker in strength, and cannot increase their 3D load-bearing characteristics, (solid material precipitation like calcination effects at the fractures and inner surfaces of the conduits due to groundwater circulations), they collapse according to their 3D rock failure conditions. Earthquake vibrations, changing the induced stresses and groundwater conditions, and pore pressure differentiation due to changes in rock gasses & groundwater reservoir conditions have influenced these collapses and their rate of occurrences in geological time periods.

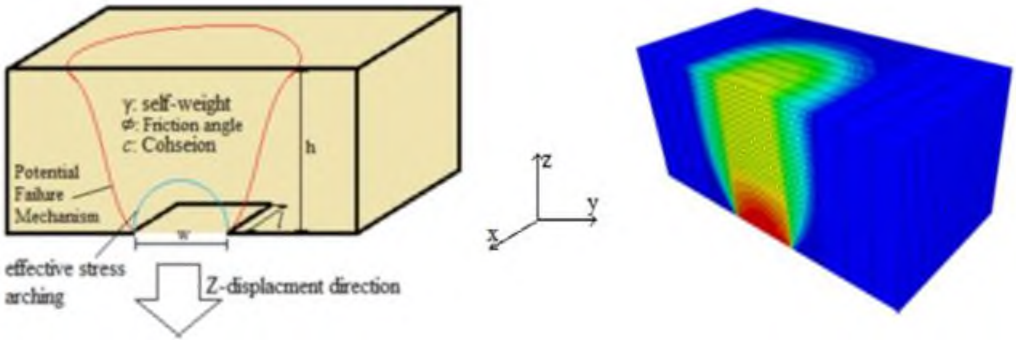


Figure 7. Subsidence (sinkhole cavity) model idealised for numerical FLAC 3D analyses and resultant velocity contours obtained (for the case of; h/w=2, w/l=2, $c_u/\gamma D$=1.05), [22].

4. ANALYSIS OF STRESS-STRAIN CONDITIONS AROUND A HYPOTHETICAL SINKHOLE

Underground spaces (in micro/macro scales) are widespread in earth crust. Their occurrences are vital for the creatures living on earth. Groundwater and other liquids and gasses occupy the pores & cavities of earth crust for their reservoir locations. Their time-dependent chemical and physical processes (under high overburden earth pressure) have continued there according to the depth of deposition as well. Initiation of micro scale cavities through rock fractures, and rock property alterations after their chemical weatherings are expected features for all celestial planetary rock crust which have their gravitational force. As far as there is no human activities around subsidence & sinkhole areas, these cavity collapses related to ground surface morphologic differentiations might be accepted as normal features. However, human urbanisation areas, crop fields, forests, etc. have required stable ground dynamics. Displacements even in the micro-scale which were realised at the base of them have caused damages on their structural conditions in time. For instance, the ground surface at Konya Plato (Turkey) has developed flat landforms at the centre of the region. The rock masses and related rock formation units have formed according to the conditions of geological eras and the regional morphology has shaped with ongoing volcanic, tectonic, and sedimentation activities. Types of rock masses and; their thicknesses, angular settlements, layers, fractures, cavities, weakness zones, etc. are all related to those activities and climatic conditions (differentiations) in geological eras. The resultant rock masses are reported through research [24; 26, 27] with related "rock-formations" and their geological eras as stratigraphic columns. Ulu reported that Insuyu-formation which is Miocene-Pliocene era rock consist of sinkholes in Konya region [25, 26, 27] has *conglomerate, sandstone, siltstone, claystone, marl, limestone, platy limestone, tuff, ignimbrite, and chert rocks*. The stratigraphic section obtained for the Karapinar (Konya) region was supplied by Törk et al., [29; 30] as well. Miocene aged Insuyu rock formation contented rocks are listed here as; *red conglomerate, sandstone, mudstone, chert, limestone, dolomitic limestone, micritic, marl, platy limestone, claystone, conglomerate, Ignimbrite, tuff, claystone, mudstone, and lacustrine limestone*. The other rock formations over the Insuyu-formation were listed (with their rock contents) as follows, [30]; Insuyu-formation had first been over-layered with Pliocene aged Karacadag-formation (*agglomerate, andesite, basalt, dacite, riolite)*. Then, Kilavuztepe-formation (Pliocene) had formed over them with its *basalt* rocks. Incesu-formation has a transition time between Pliocene and Pleistocene era, and it consists of *conglomerate, sandstone, claystone, mudstone, lacustrine limestone*. Pleistocene era rock formations were formed over Incesu-formation one over the other as follows: Akviran-formation (*conglomerate)*; Karapinar-formation (*pyroclastics of maar, basalt, stag*); Divanlar-formation (*gravel, sand&mud*): Tuzgolu-formation (*gravel-sand, silt-clay, clay with gypsum, clay with limey, sand&silt, clay&sand with organic soil*); Koymatyayla-formation (*gravel&sand, silt with carbonate, silt&marl with sand*); Hotamis-formation formed during Pleistocene and Holecene era. Its Pleistocene aged rocks are listed as; (*gravel&sand, sand with gravel, silt, clay, lignite, sand&gravel, silt&clay with carbonate, gravel&sand*), Hotamis-formation's Holocene era rocks are listed as; *clay with organic soil or soft clay*. Other Holocene era rock formations are Taburici-formation (*wind sand-dunes*), and Traverten-formation (*travertine*). The rock types at *debris rocks, alluvium, alluvial fans* are the latest rock types listed by Törk et al., [30]. The rock type images near the ground surface can also be observed at sinkhole photos which were taken at Konya, Turkey. As it is seen from the photographs (Fig. 8), the rock masses below the ground surface at the sinkhole region of Konya are layered rocks and their stratifications were listed through the works performed by Törk et al., [30]. Groundwater levels can also be observed at some of the sinkholes collapsed in Karapinar, (Konya) region (Fig. 8c).

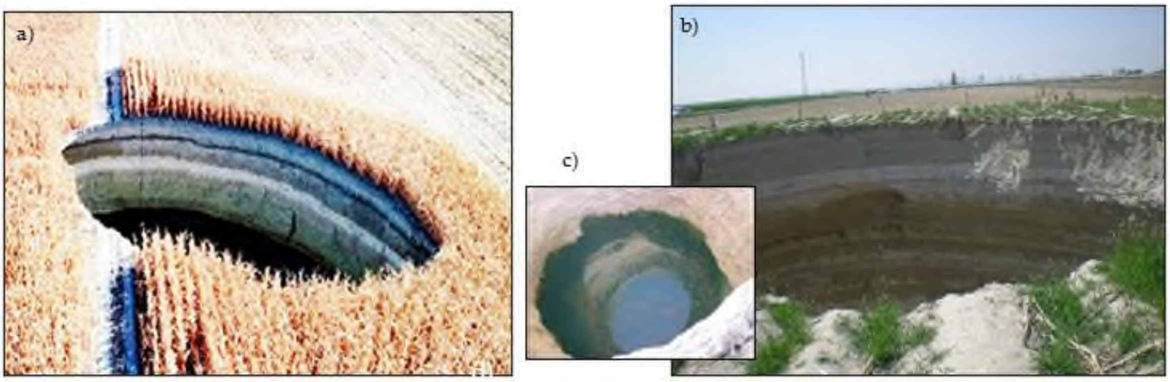


Figure 8. a) Rock layers just below the ground surface at a sinkhole formed at a cornfield in Sep.2018 (Konya), [31]. b) Rock layers at Yarimoglu sinkhole, collapsed in Dec. 2008 at Karapinar-Konya, [32], c) Groundwater level observed at the bottom of the Yarimoglu sinkhole (in May 2009), [32].

Rock mechanics behaviours of the layered rocks listed through stratigraphic sections require complex & comprehensive research. Underground conduits/spaces which groundwater can be deposited or flow through could be in different sizes and shapes. Underground water reservoirs, passage routes, conduits might also come across faults, fracture zones, weakness zones, etc. to initiate upward caving procedures to form overburden caving activity described like in Fig. 5, [17] and Fig. 6b, [21]. Possible chimney type sinkhole progress could happen step by step in time as it is illustrated in Fig. 9. This figure presents hypothetical sinkhole development phases that occurred due to mechanical property deterioration which could be directed by induced stresses, rock masses' property differentiation and groundwater influences. In order to visualize the mechanical property influences and groundwater effects together with cavity size variation, in this preliminary education targeted study, two types of hypothetical material models (two scenarios) were handled through numerical FLAC 3D v6.0, [33], solutions. In the first scenario, one type of low strength, uniform, homogeneous rock mass around the small sized cavity which tends to provide chimney type sinkhole was modelled as a massive rock material which deforms according to Mohr-Coulomb failure criteria. Input data facilitated for this step of the analysis are supplied for 40x40x40m cubic volume, ($64000 m^3$), which the calculation mesh was arranged to simulate deep sinkhole cases' (>40m), observed at Karapinar, (Konya), region like Yarimoglu sinkhole. Most of the sinkholes observed at Karapinar region have their depths, [29], less than 40m. Dursun wrote that 7 out of 52 sinkholes have their depths more than 40m, [29]. In this preliminary hypothetical study, numerical modeling techniques used were conducted to simulate sinkhole formation and assess its effects on surrounding rock mass deformation and stress fields through two scenarios. For the first scenario, soil and limestone units were layered above a defined water table at a depth of 30 meters. Sequential cavings happened at these layers simulate sinkhole progression in the hypothetical model in the first scenario. In the second scenario, additional horizontal rock layers were introduced within the same geometric framework, enabling a comparative analysis of displacements and stresses under varying multi-layered rock mass conditions. In these models, each rock material type, unit, (i.e.: soil, limestone, silty clay, and sandstone, etc.) was assigned a Mohr-Coulomb failure criterion, with specific mechanical properties, (*such as: density, elastic modulus, Poisson's ratio, friction angle, cohesion, and tensile strength),* informed for low strength rock properties in general, [34, 35]. Fluid properties were activated by using the "fluid" module in FLAC 3D, assigning permeability and porosity for each rock type to reflect natural fluid behavior. Boundary conditions were applied to restrain normal displacement velocities along the side surfaces, with zero-velocity conditions at the top and bottom surfaces to stabilize the model. The water table was represented by a fluid plane defined at 30m depth of the model (which has 40x40x40m dimension) with a normal vector (0, 0, -1), establishing an underground water source with pore pressure conditions allocated to layers below this plane. Pore pressure and saturation were initialized to handle modelling of the hydrostatic effect at this depth. Through stepwise excavation and monitoring, sinkhole evolution was simulated in both scenarios, with outputs captured to analyze the stress and deformation patterns resulting from sinkhole formation. The results of numerical models by using FLAC 3D software are obtained for hypothetical sinkhole cases which simulate deep sinkhole cases are illustrated in Fig.10-14. Induced displacement levels are presented for the vertical directions of the models in Fig. 10. In similar manner, induced stress levels differentiations in vertical axis are also presented in Fig. 11. The second scenario of the hypothetical sinkhole model analysis included 3D rock layer modelling which has horizontal rock layers (massive & uniform) in the model, (Fig. 12). The resultant vertical displacement (Fig. 13) and vertical stress differentiations (Fig. 14) are then plotted to evaluate the differences with respect to 1st scenario results. Hypothetical models which are used in this study are actually an engineering attitude to model the complex rock mass structures observed at Karapinar regions. As the general stratigraphic sections supplied by Ulu [26, 27] and Törk et al., [30] illustrated that rock masses in the Karapinar (Konya) region have their layered characteristics with their different values of thicknesses. In order to approach more realistic 3D rock mass modelling for the Karapinar region, inclusive studies should then be scheduled to obtain mechanical properties of each rock mass encountered through the unique rock-formations belonging to this region. The research most probably will include several drill-holes to collect enough rock carrot samples to determine rock masses' thicknesses, depths, mechanical properties, porosities, permeability, etc. for observed stratigraphic rock masses.

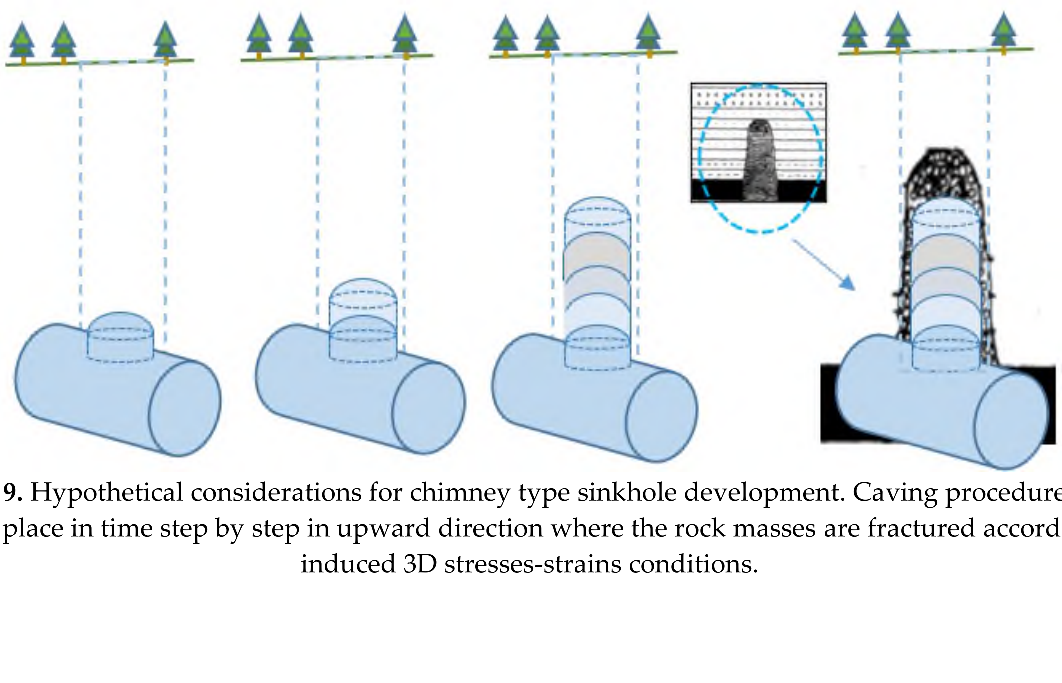


Figure 9. Hypothetical considerations for chimney type sinkhole development. Caving procedures have taken place in time step by step in upward direction where the rock masses are fractured according to induced 3D stresses-strains conditions.

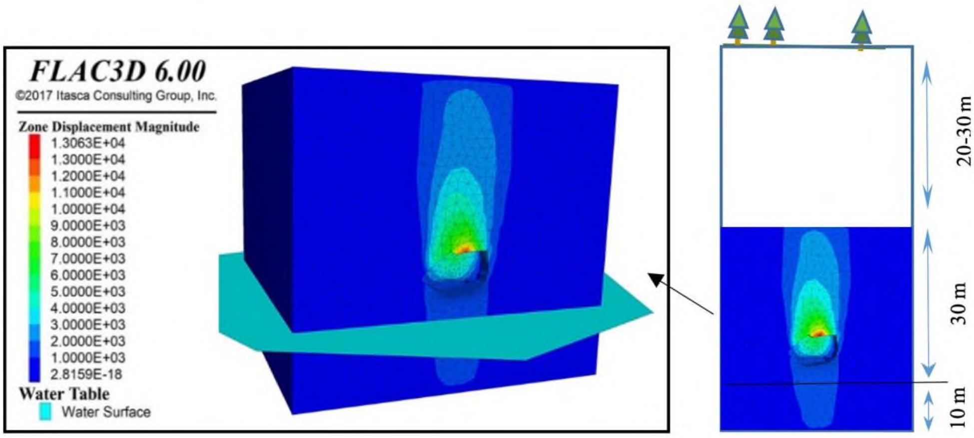


Figure 10. Induced displacement zone values (in mm) for the 1st case scenario modelled through FLAC 3D for hypothetical small scale roof cavity of groundwater conduit tending to develop sinkhole.

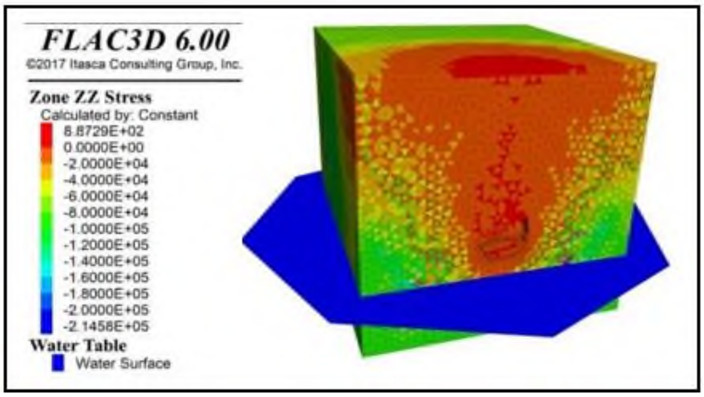


Figure 11. Induced vertical stress (in Pa) distributions for the 1st case scenario at the modelled hypothetical sinkhole development through FLAC 3D start from small scale roof cavity of groundwater conduit tending to chimney type sinkhole.

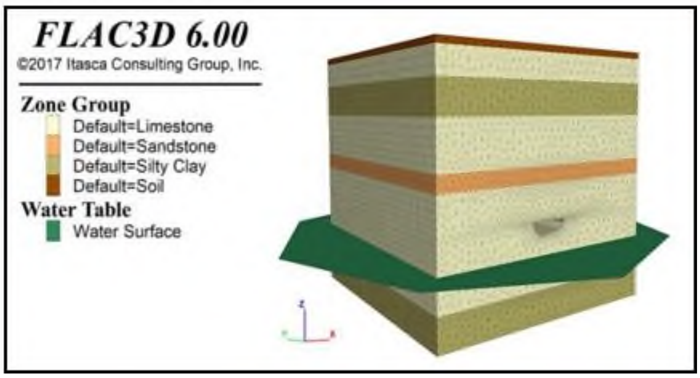


Figure 12. Hypothetical layered rock mass modelling example for the analysis of 2nd scenario through FLAC 3D analyses.

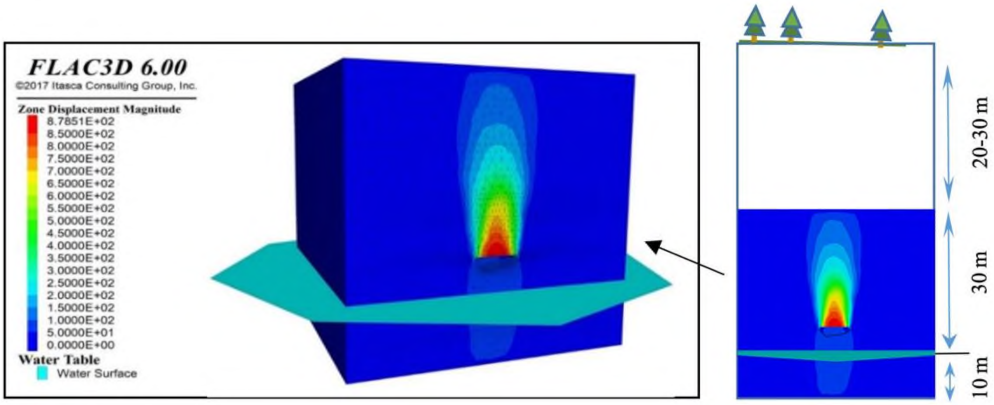


Figure 13. Induced displacement zone values (in mm) for the 2nd case scenario modelled through FLAC 3D for hypothetical small-scale roof cavity of groundwater conduit tending to develop sinkhole.

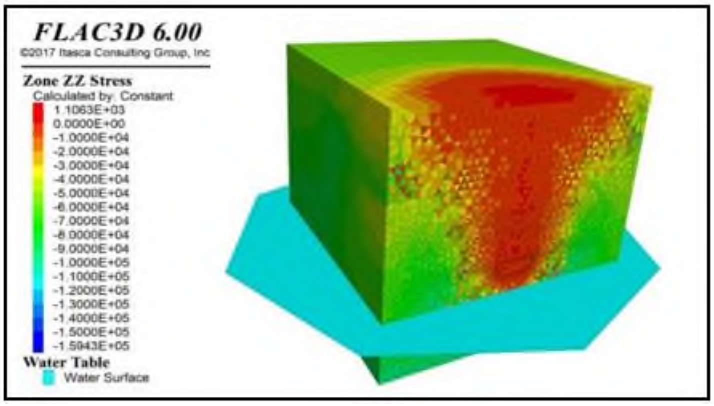


Figure 14. Induced vertical stress (in Pa) distributions for the 2nd case scenario at the modelled hypothetical sinkhole development through FLAC 3D start from small scale roof cavity of underground groundwater conduit tending to chimney type sinkhole.

5. CONCLUSION

Underground spaces micro and macro scale in dimensions are widespread in earth crust. Their stabilities concerns are not only related to their structural healths and safety but also the stabilities of overburden layers which have potential danger of caving due to their collapses. Underground mining spaces, natural rock pores, voids, cavities, caves, all types of civil subterranean spaces etc. have their potential to initiate subsidence & sinkholes. Mechanical behaviours of the rock masses in the fields are difficult to estimate due to their scales, and uncertainties encountered. Laboratory rock material test results and their evaluations supply valuable data but they have their limitations for the real-world rock mass cases. When the problem encountered by engineers is sinkhole collapse and its development, sinkhole occurrences and their developments for certain regions are required to be analysed through rock mass mechanical behaviours. Roof failure analyses supplied for underground spaces are the starting point in these kinds of analyses. Rock fracturing, fracture initiations and propagations according to induced stresses around the cavities are directing research fields to be followed. Numerical analyses supply also data & results for engineering decision circumstances. Preliminary numerical analyses handled here to understand the stress and displacement distributions around sinkhole cavities. Massive rock mass consideration was enhanced here with massive horizontal rock mass layer additions to the hypothetical sinkhole models to visualise the stress and deformation differentiation. Engineers should follow rock mechanics procedures to evaluate subsidence and sinkhole developments and their dangers on economic assets (urban areas, crop-fields, forests, etc.). Comprehensive researchers including drill-holes to obtain carrot samples from each geologically named rock-formation below the targeted land parcels could be required for further rock mechanic analyses to handle more representative input data for numerical analyses. Decreasing the uncertain features of the rock strength properties and rock discontinuity set related parameters, provide more realistic results in conceptual and numerical analyses. Thus, collecting representative input data and modelling the sinkhole host rock masses in a more realistic manner helps to evaluate sinkhole occurrences at Karapinar (Konya) region as well.

Declaration of Ethical Standards

The authors declare that the study complies with all applicable laws and regulations and meets ethical standards.

Credit Authorship Contribution Statement

M.Kemal GOKAY: Methodology, Conceptualization, Resources, Investigation, Writing, Review & Editing, Supervision.

Mehmet MESUTOGLU: Methodology, Conceptualization, Resources, Investigation, Writing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data Availability

Data will be made available on request.

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