THE EFFECT OF COLLAPSE OF UNDERGROUND OPENINGS ON GROUND SURFACE THROUGH MODEL EXPERIMENTS AND CASE HISTORIES

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The effect of underground mining, particularly by long-wall mining, on the ground surface is well known. There are also many case histories on the formation of sinkholes by man-made underground openings and natural cavities in karstic and volcanic areas. When new structures are to be built over or below existing natural or man-made cavities, the possible effect of collapse of underground openings on ground surface is very important for the design of new structures. The authors present the outcomes of model tests and collected case histories on the effect of collapse of underground openings on ground surface. Furthermore, some guidelines are proposed how to evaluate such surface effects in relation to the size and depth of underground openings.

Key Words : *collapse, underground openings, ground surface,subsidence, settlement.*

1. INTRODUCTION

The construction of new structures over or beneath areas having man-made underground openings or natural cavities has been increasing in recent years. For example Shizuoka Airport was constructed over a tunnel of Tokaido Shinkansen railway. Similarly, New Ishigaki Airport was built over an area having karstic cavities, in which precious bats live and such cavities have to be protected[1)]. There are also several examples of highways and railways built over lava tubes in the vicinity of Mt. Fuji in Japan, Cheju Island in Korea and Hawaii[2,3,5)]. When such underground openings or natural cavities known before the construction some counter measures can be undertaken. However, the most critical situation occurs if their existence is unknown and collapse after the construction. Collapses of underground openings may occur due to disturbance by the construction or natural causes such degradation of rock mass in long-term and/or seismic shaking[5,6)].

There are some guidelines how to consider the effect of possible collapse of underground openings on ground surface exist in some countries. However, such guidelines mostly based on soil-mechanics principles utilizing trap-door model experiments as well as some experiences from case histories. The authors have been involved with this issue for some time and carried out model experiments, analyzed case histories and performed some analytical and numerical analyses[1)]. In this study, the authors present the outcomes of model experiments and the analysis of collected case history data on the effect of the collapse of underground openings on ground surface. Furthermore, some guidelines are established for evaluation such effects on ground surface with the consideration of depth and size of underground openings. The effect of earthquakes on the enlargement of extension of the collapsed region also investigated through model experiments.

2 MODEL EXPERIMENTS

Laboratory model tests are also utilized to investigate the collapse phenomenon of ground. Trapdoor model tests are commonly used to study the loads on tunnels support. This model test technique is generally to study the effect of arching on loads on the tunnel supports. In addition to trapdoor tests, some experiments are conducted on circular tunnels by authors and described briefly in this section.

2.1 Cohesive Ground

The tube representing a rigid circular tunnel lining is gradually pulled out and the ground is allowed to fill into the model tunnel space if it fails. Under static condition, some partial collapses occur above the roof. Then models were horizontally shacked using a shaking table. During the experiments the overburden height is varied from 0.5D to 3.0D. Figure 1 shows views of models, before and after excavation.

and shaking to the base of models applied after the excavation. For an overburden ratio of 1.0. Except very shallow openings, the failure plane emanates from the sidewall of the tunnel as seen in Figure 1 and it is steeply inclined.

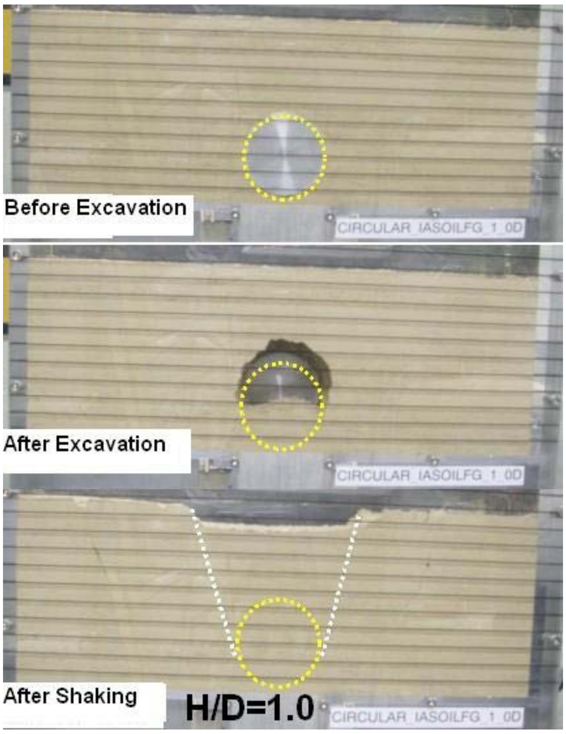

Figure 1. Views of models before and after excavation and after shaking.

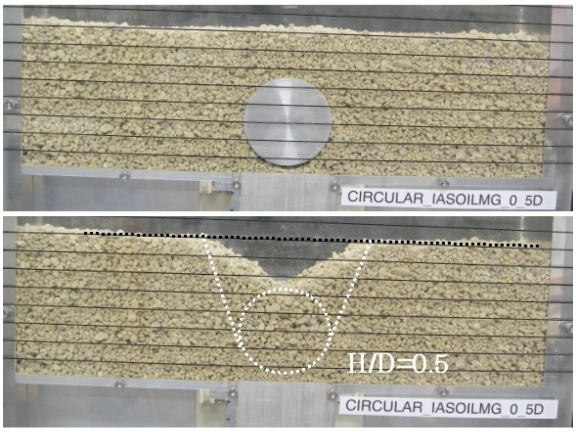

Figure 2. Views of models before and after excavation with an overburden ratio (H/D) of 0.5.

2.2 Fractured/ CrushedGround

Next models were carried out using crushed ryukyu limestone and the overburden ratio (H/D) were 0.5, 1.0 1.5, 2.0 and 3.0. Figures 2 and 3 shows some views of the models with an overburden ratio (H/D) of 0.5 and 2.0. When the overburden is quite shallow the ground surface surface has an inclination equivalent to its repose angle after the collapse of the undergound opening. However, the overburden depth increases , the failure plane is steeply inclined. The models are also subjected to horizontal shaking if surface depression increases in size after the collapse of the underground openings.

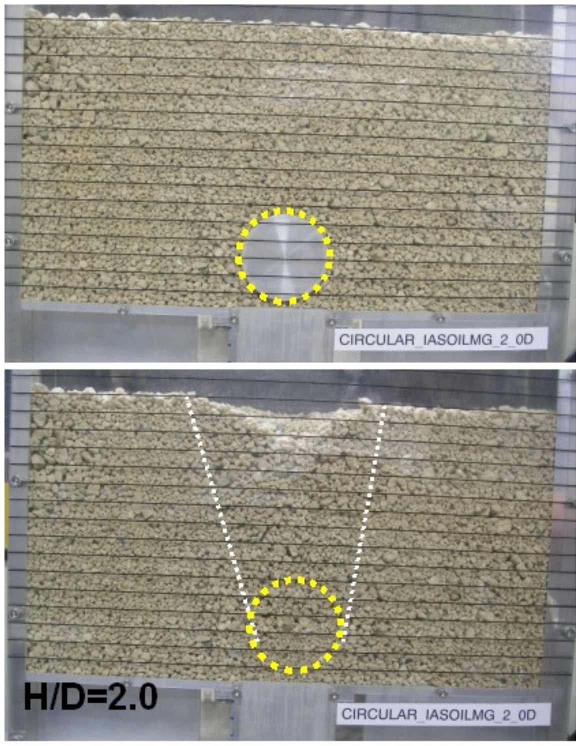

Figure 3. Views of models before and after excavation with an overburden ratio (H/D) of 2.0

Another series of experiments were carried out to see the how the collapse of tunnel might effect the underground openings above the tunnel. Figure 4 shows views of such a model test before and after the collapse of the circular tunnel. The overall overburden ratio was about 4 and the distance between the tunnel and existing cavities above the tunnel was about 1.1D. The overall response is quite similar to the previous experiments without such pre-existing underground cavities. Nevertheless, the area of influence become larger.

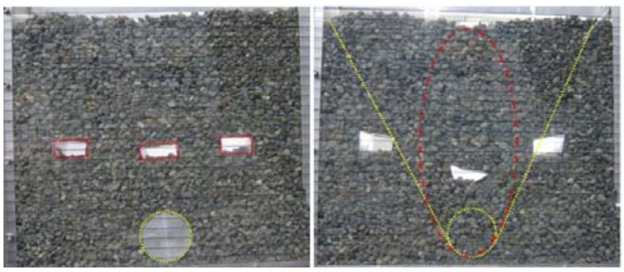

Figure 4. Views of models before and after excavation with an overburden ratio (H/D) of 4.0 and pre-existing cavities above the tunnel.

2.3 Layered and Jointed Media

A series of model tests on rectangular or circular tunnels in a layered rock mass model with cross joints (intermitent pattern). The model material has similar characteristics explained in the previous section.

The inclination of layering was varied out in experiments. Figure 5 shows an example of collapse of rectangular underground opening in jointed rock mass. Figure 5 also shows an illustration of collapse mechanism of rectangular undergound openings in layered and jointed rock mass models. When intact material does not break under induced stress field, such openings generally fail when the excavation width becomes equal or greater than the overburden.

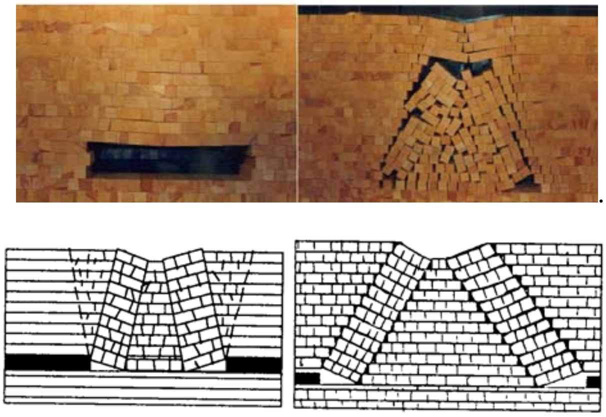

Figure 5. Views and illustrations of a rectangular underground openining in layered and jointed rock mass model.

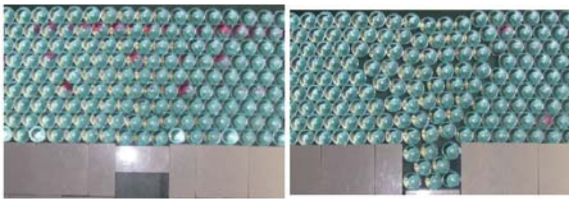

Figure 6. Views of models before and after excavation with an overburden ratio (H/B) of 2.0 using glass-beads as model ground.

2.4 Trapdoor Experiments

A series of trapdoor experiments are carried out on underground openings in a model ground consisting of glass beads, aluminium bars, crushed limestone and sandstone, granular materials using a base-friction model testing apparatus or vertical see-though 1g gravity model testing apparatus by changing the overburden ratio (H/B). Figure 6 shows views of the model before and after testing using a base-friction model testing apparatus. The ratio of opening width to diameter of the glass beads was about 3. As noted from the figure, a mass of glass beads moves towards the opening and two steeply inclined failure planes emanated from the coners of the opening. Although some arching actions do occur within the failed body, the movement occurs until the lowering of the trapdoor is terminated.

Similar experiments were carried out using see-through 1g model testing apparatus. Figure 7 shows two examples of model experiments with an oberburden ratios (H/B) of 1.0 and 2.0, respectively. The ratio of opening width to diameter of the glass beads was about 16. Although the particles were smaller in size, the fundamental behaviour observed was quite similar to the previous model experiments with glass beads. It should be noted that the particles can freely rotate and move compared with sugare-like discontinuity patterns.

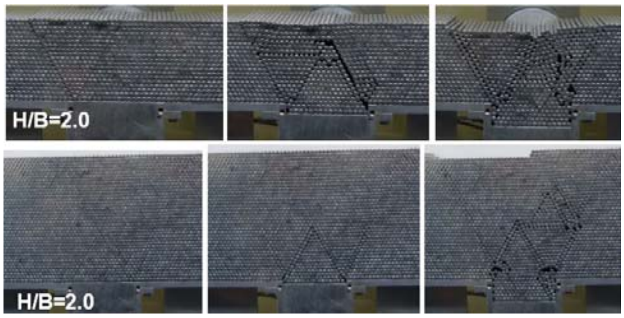

Figure 7. Views of models before and after excavation with an overburden ratio (H/B) of 1.0 and 2.0 using aluminium bars as model ground.

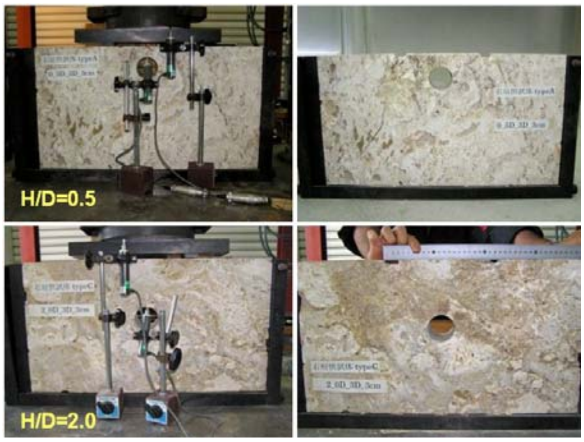

Figure 8. Footing tests on Ryukyu limestone blocks having circular cavities.

2.5 Model Experiments under Surface Loading

There may be some cases to protect undergound openings due to overburden loading resulting from the dead-weight of embankment materials or construction as seen in the examples of constructions of Shizuoka and Ishigaki Airports. The major issue is how to select the width of protection slabs or arches in such cases. The authors have carried out a series of models tests of circular or rectangular underground openings excavated in the Ryukyu limestone blocks. Figure 8 shows views of two model tests. When the overburden is small, the failure plane reached the opening. However, for overburden ratios greater than 2, the failure does not directly involve underground openings.

3 CASE HISTORIES

3.1 Collapse of Natural Cavities

Natural cave collapses often occur in karstic regions all over the world (Figure 9). In addition, mining and tunnelling activities may also cause collapses. In this section, several examples of natural cave collapses and collapses due to mining and tunnelling activites will be presented, separately.

Figure 9. Examples of collapses of karstic caves

Large karstic regions exist in various parts of the world . Rock mass consists of high calcium carbonate content and it is easily dissolved in the acids produced by organic materials. About 10% of the 15% of the land in the United States surface consists of soluble limestone, which can be easily dissolved by the weak solution of carbonic acid found in underground water. When enough limestone is eroded from underground, a sinkhole (also called a doline) may develop. Sinkholes are depressions that form when a portion of the lithosphere below is eroded away. Sinkholes can range in size from a few feet or meters to over 100 meters deep. Karst topography forms the world's longest cave system. the Mammoth Cave system of Kentucky is over 560 km long. For the Sinkhole Plain in central Kentucky, there are approximately 5.4 sinkholes per square kilometer over a 153 square kilometer area. For north Florida there are almost 8 sinkholes per square kilometer over a 427 square kilometer area [4)].

Karst topography can also be found extensively in the Shan Plateau of China. Tiankeng (skyholes in Chinese) occur in thick limestones that have been sculptured into cone and tower karst landscapes. The tiankeng are vertical-walled depressions with depths ranging from 100 to more than 300 meters. Diameters are variable but are typically in the range of hundreds of meters.

Gunung Mulu National Park near Miri, Sarawak, Malaysian Borneo, encompasses incredible caves and karst formations. The park is famous for its caves. Within Gunung Mulu National Park is the world's biggest natural enclosed space - Sarawak chamber, found in Gua Nasib Bagus. It is 700 m long, 396 m wide and 70 m high..

There are many karstic caves in Japan. They extend from Iriomote Island to Hokkaido. Most of these karstic caves are in the close vicinity of Median Tectonic Line. The faulting induced by this tectonic structure played major role in the formation of these caves. One of the most famous karstic area is called Akiyoshido plateau. The Akiyoshi plateau or Akiyoshidai, is a 130 square kilometre area of karst topography in Yamaguchi Prefecture at the extreme western end of Honshū island, Japan .

There are many karstic caves in Ryukyu Islands and they are mainly located in Ryukyu limestone formation. One can easily notice the collapsed parts of the natural caves in many locations. For example, Nakabari cave in Miyako Island, Sabichi cave and C-cave in Ishigaki Island, Toriike in Irabu Island are some examples of the collapsed natural caves (Figure 10).

Figure 10. Examples of sinkholes in Ryukyu Islands

3.2 Collapse of Man-made Underground Openings

Longwall mining and block caving methods are based on the principle of inducing the failure of ground above the mines (Figures 11). Therefore, they may represent ultimate form of failure of rocky ground above the mines and it is generally called the subsidence of the ground.. The break angle defines the failed zone and draw angle define the angle of plane beyond which for both h the ground subsidence do not occur. These two planes are generally conjugate to each other and their inclination ranges between $60-75^{o}$ depending upon properties of the ground above.

Room and pillar technique is also used to excavate ore from ground and the ground above is supported by pillars left. Weathering and degradation of rock as well as man-made activities on the ground surface may cause the collapse of roof as well as pillars. When the overburden is shallow, they form sinkholes (Figure 11). On the other hand they may cause ground subsidence on the ground surface when they are deep.

Figure 11. Surface depressions due to collapses of man-made underground cavities.

Figure 12 shows several examples of ground failures above the room and pillar workings in Nagakute and Mitake towns where abandoned lignite mines exist. These ground failure took place after about 40-50 years passed over the termination of mining activities.

Figure 12. Formation of sinkholes and subsidence above abandoned lignite mines

Tunneling may also induce the ground failure as seen Figure 13).

This failure form is generally observed when ground is weak or highly jointed. Furthermore, the excessive water inflow into tunnels may induce very large ground subsidence as observed during the excavation of Nakayama Shinkansen Tunnel.

Figure 13. Surface depression due to the collapse of Shinkansen tunnel

The earthquakes can also induce collapse of underground openings and/or enlarge the failed zone[5,6)]. For example the 2011 Great East Japan earthquake caused numerous sinkholes and subsidence problems at 327 locations. Even the sloshing of the undeground water in inclined shafts caused the failure of roof rock resulting in sinkholes.

The settlement of back-filling material of in shafts of abandoned quarries and mines can occur if the back-filling material was non-cohesive. Such examples were observed at several locations during the 2011 Great East Japan earthquake[6)].

4 DISCUSSIONS OF DESIGN PRACTICES

The authors compiled the results of model experiments as well as actual observations on natural caves and underground excavations. These observations are plotted in Figure 14. The horizontal axis is the ratio of depth over the bottom width of the collapsed structure (D/W_b). The vertical axis is the ratio of surface width of disturbance over the bottom width (W_t/W_b). In the same figure three functions are plotted. The first and second functions have the same functional form while the value of influence angle has different values. The value influence angle for complete trapdoor situations is equivalent to the repose angle of ground. In other words, it is expected that the shape of the non-cohesive ground above rocky base may be represented by this particular situation. The influence angle greater than the repose angle would be generally valid for underground openings, which are fully filled by the collapse material upon the failure.

$$\frac{W_t}{W_b} = 1 + \frac{2}{\tan\alpha}\frac{d}{W_b} \qquad (1)$$

The third equation, which is given below, has also a similar form except the minus sign.

$$\frac{W_t}{W_b} = 1 - \frac{2}{\tan\beta}\frac{d}{W_b} \qquad (2)$$

The equation above would corresponds to ground failure which are not reaching the ground surface. They may be representative of the failure of ground around deep underground openings. In the same figure, the design value used in the construction of New Ishigaki Airport is also plotted.

Results of trapdoor model experiments generally follow the Equation (1) for the repose angle of 30^o. Results of circular model tunnel experiments in granular medium generally obeys Eq. (1) with an influence angle greater than 60^o. Nevertheless, experimental results do not follow this linear trend, which means that the influence angle differs depending upon the depth of underground opening. Eq. (2) also provides a lower bound to experimental or observational results. This function becomes negative after a certain depth. In other words, the failure of ground around the opening may not reach to the ground surface after a certain depth. As noted from the figure, the new design value is conservative for depths up to a depth ratio of 1.74 and becomes non-conservative thereafter if the ground is granular. However, if the ground is cohesive and frictional, the influence of ground failure on the ground surface gradually disappears. In other words, the design value may provide an upper bound value for cohesive and frictional ground in view of observations on actual cave collapses and model tests and it may said that it is on safe side. Nevertheless, it should be noted that this conclusion is only valid for structures failing under the action of gravity. If loads other than gravity act on the underground openings, the assumption made in the design value may not be true.

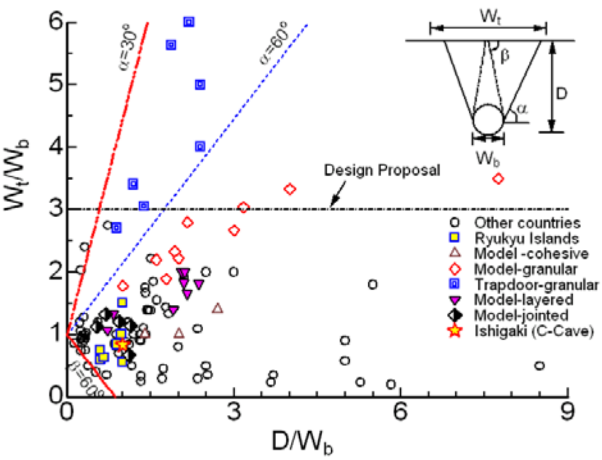

Figure 14 Comparisons of empirical functions with results of observations and experiments.

5 CONCLUSIONS

Some empirical equations were developed and they were compared with the results of observations as well as experiments. Furthermore, the validity of the design value used in practice was also discussed with the considerations of the results of experiments as well as of observations. From these comparisons, the following conclusion may be drawn:

If the ground is cohesive and frictional, the influence of ground failure on the ground surface gradually disappears. In other words, the design values adopted in practice may provide an upper bound value for cohesive and frictional ground in view of observations on actual cave collapses and model tests and it may said that it is on safe side. Nevertheless, it should be noted that this conclusion is only valid for structures failing under the action of gravity. If loads other than gravity act on the underground openings, the assumption made in the design value used in practice may not be true.

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地下空洞陥没の地表面に与える影響に関する模型実験および事例分析による検討

藍檀オメル、渡嘉敷直彦

自然空洞（鍾乳洞,火山洞など）,廃鉱,廃坑,廃地下採石場などが陥没した場合,その影響は陥没した空洞の深さ,幾何学形状,周辺岩盤・地盤の性質などによって大きくことなる.また、静岡空港の直下における新幹線トンネルや,新石垣空港の直下における自然空洞に対しての対策工法として建設されたアーチ構造のフーチングスパンを決定する際に地下の空洞の影響についての考え方が様々であった.実務では、土質力学における落とし戸の理論・実験に基づいてその影響を決定することが多い.しかし、空洞が深くなると,落とし戸の理論・実験に基づいて決定される影響範囲がかなり大きくなり,設計上様々な問題が発生する.本論文では、著者らが行った様々な模型実験および事例分析結果に基づいて地下空洞陥没が地表面に与える影響について検討し,定量的に影響範囲について提案し,その妥当性を検証した.