# STABILITY ANALYSES ON THE DISSOLVED CAVITIES OF QIAOHOU SALT MINE

# ANÁLISES DA ESTABILIDADE NAS CAVIDADES DISSOLVIDAS DA MINA DE SAL DE QIAOHOU

Yu, Xianbin, *Associate Professor, KUST, Yunnan, China; Post-doctorate, Centro de Geotecnia, IST, xianbin@ist.utl.pt*
Dinis da Gama, Carlos, *Centro de Geotecnia, IST, Lisboa, Portugal, dgama@ist.utl.pt*

## ABSTRACT

Qiaohou is a mine located in sedimentary-metamorphic salt deposits at the Yunnan province of China. Since the 1960's, a technique named "drilling well dissolution" was adopted in the mine to exploit rock salt by supplying fresh water into the cavities and transporting the saline solution to surface. In 1989, the drilling well having the maximum diameter collapsed and produced many losses on properties, making further exploitation difficult.
In this paper, numerical simulations were performed to analyse the stability of the dissolved cavities of this mine with the code Phase 2, a finite element program with elasto-plastic functions. The relationship between the underground cavity sizes and their stability was investigated and is described.

## RESUMO

A mina de sal de Qiauhou está situada em formações sedimentares metamorfisadas da província de Yunnan, China. Desde 1960, tem sido utilizada na mina, a técnica de dissolução para explorar o sal, injectando água fresca por furos de sonda nas cavidades subterrâneas e transportando a salmoura para o exterior. Em 1989 ocorreu um colapso na extracção de salmoura que ocasionou muitos danos à superfície, num poço perfurado de grande diâmetro.
Neste artigo descrevem-se simulações numéricas que foram executadas para analisar a estabilidade das cavidades dissolvidas da mina, com o programa Phase 2, elementos finitos que tem funções elasto-plásticas. A relação entre as dimensões das cavidades e a sua estabilidade foi investigada e é objecto desta descrição.

## 1. INTRODUCTION

Qiaohou is a sedimentary-metamorphic deposited salt mine, located at Yunnan province, south-west of China. The deposit appeared to be approximately a layer with changeable width and the average thickness of the orebody (rock salt) is about 30 meters. However, its vertical thickness at the local area of mining is as high as 60 to 100 meters. Salt contained in the rock salt is a little more than 50%.

It has been several hundred years that people took rock salt from the deposit and made it into salt, although the mining operation had always been conducted by manual works and so the outputs were always very small. Beginning from 1950's, some modern equipment and underground mining system were adopted to extract rock salt from underground stopes with a room and pillar method, a system been called "dry mining" in this mine. In 1960's, a dissolution technique named "cave dissolution" was adopted. With the new technique, the rock salt was no longer mined and transported, the transportation of the ore was replaced by transportation of the saline solution. Water was pumped into the rock caves and then saline solution was pumped out to the plant to make salt. However, with the cave dissolution, the shape of the dissolved cave was developed naturally and could not be controlled, making the roof area of the stopes more and more large and the dissolved cavities unstable. Roof failure happened during the following period of the exploitation. A few years later another technique named “drilling well dissolution” was then employed, with which the geometry of the cavities can be controlled and dissolved into cylinders. With the drilling well technique, the solved cylinder cavities are more stable, and the production has higher extraction recovery and higher efficiency, making the mining cost decreased and the output increased. This technique is then employed until present time. As water is employed in dissolution process, the technique is called “water mining” in this mine.

At the beginning period of drilling well mining, the diameters of the well were only 15 meters. Later, the diameters were increased to 30 to 50 meters. For drilling well No. 12, the diameter reached to a high value of 77 meters.

When exploited with room and pillar system, the stopes kept stable and collapse was hardly appeared, because both the span and the volume of the stopes were relatively small and the ore recovery was quite low. With the dissolution technique, the volumes of the cavities were much bigger. For some cavities of the cave dissolution, the exposed areas of the cavity roof were as high as $1500m^2$ to $2000m^2$; for the cavities of the drilling wells, the exposed roof area was even larger. So local collapses had happened several times.

In December 1989, a large collapse arisen at drilling well No. 12, the main production drilling well during late 1980’s. At the moment of the collapse, 80,000 $m^3$ of the saline solution was driven away from the cavity of the drilling well. The saline solution emerged out to surface through level 4, and went passed the salt plant. Some equipment in the plant was damaged. Fortunately the collapse happened during the night and no people were injured. After that, a cave with a geometry of approximately cylinder appeared on the surface with the diameter of about 40m and depth about 15m.

In this paper, numerical simulations are conducted with the finite element program Phase 2 to analyse the stability of the drilling wells of Qiaohou salt mine, to investigate the best geometry of the drilling well cavities.

## 2. GEOLOGY AND SIMULATION MODELS

The rock salt and the country rocks are composed of the Jurassic strata. Rock salt is stable and support is unnecessary when underground drifts are excavated in it. Most of the country rocks are composed of mud-conglomerate containing richly gypsum and salt, and are usually very weak, especially exposed to air after drifts have been excavated through them. So supports are necessary for all drifts excavated in the country rocks. Usually the deformation of the drifts in country rocks is quite large, making the supports fail gradually, thus, the supports have to be renewed every 1 or 2 years.

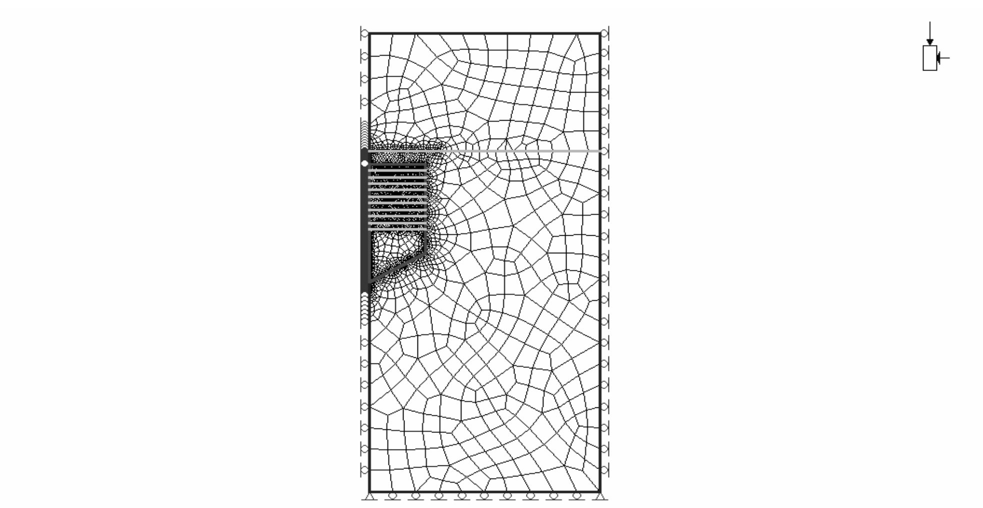
In the exploitation of this mine, the dissolved cavities must be well controlled and cannot reach roof rocks since the roof is so week, or else failure would appear immediately, making the following excavation difficult. Therefore, for the sake of keeping working safety, the operation cave of the drilling well, where the exploitation equipment is installed, has to be excavated in rock salt. Then the roof of the dissolved cavity cannot reach overlying of the rock salt during the upward dissolution, some rock salt have to be remained unsolved to protect the stability of the cave and then the stability of the equipment and working people. The rock salt remaining on the roof of cavities (i.e., the rock salt between cavity roof and the overlying rock), is called “floor” (roof pillar). Obviously, with the reason of economy, the thickness of the “floor” should be as low as possible; however, for the sake of safety, the thickness should have enough thickness. For the purpose of keeping balance between economy and safety, investigations on the suitable value of the “floor” thickness are important. Unfortunately, such a work has not been conducted up till now and the thickness values of the “floor” adopted are completely experience values without supported by further investigations. The authors believe that this was the most important reason that produced the accident of 1989.

Measurement results of convergence (relative deformation) and settlements were conducted and continued during several years in the underground drifts of Qiuaohou salt mine. The obtained results shown that the vertical convergence in these drifts were larger than the horizontal one and the ratios between the vertical and the horizontal convergence are between 1.65 and 7.86 (Yu et al. 1994). Considering the influence of the excavated cavities near by, the largest ratio value should be removed and the average ratio between vertical and horizontal convergence should be approximately 2. This number means that the stress field in the rock mass of the mine is of the gravity type and vertical component of the initial stress is larger than the horizontal component. Such a result supplies an important data for the numerical simulation concerned with this paper.

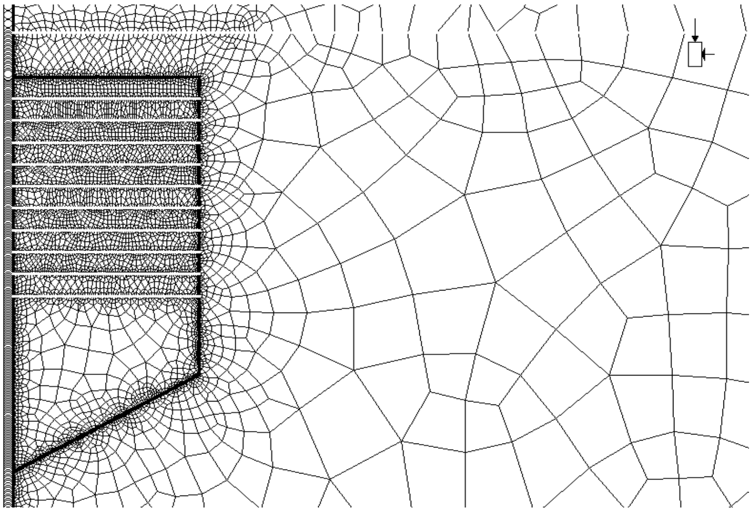
Finite element program phase 2 was adopted to make the numerical simulations. Since the geometry of the dissolved wells is cylindrical, non-linear axial symmetry simulations were performed.

Simulations were performed to analyse the stress distribution and stability of the drilling wells with different diameters, mainly the diameters of 40 m, 50, 60 m and 77 m. Fig.1 shows the mesh and the boundary conditions of a simulation model, of which the diameter was 77 m (drilling well No.12). Two materials are existed in this model: mud-conglomerate (on upper part) and rock salt (situated below). In the simulations, pressure normal to the tangent direction was acted on the inner surface of the dissolved cavity, to simulate the air pressure used to make the dissolved solution out of the cavity automatically. The other models were similar.

In the simulations, the elements at the lower part of the cavity were supposed to be dissolved first, then dissolution continued upward in the following simulation stages, to observe the results of the excavation process.



(a) Simulation model and the boundary conditions



(b) Detail mesh around the cavity

Fig.1 – Simulation model with the mesh

## 3. MAIN RESULTS AND DISCUSSION

After a dissolution cavity is formed, stress concentration with large values appears at the sharp corner of the cavity and would cause local failure there. However, the stress concentration area (volume) of such compressive stress is small and is not important to the total stability of a cavity. Tensile stress is more important and needs detail investigation.

Fig.2 presented contours of tensile stresses ($s_3$) appeared in the rocks after the first excavation stage was finished under the condition that the diameter of the drilling well is 77m. At this moment, the vertical distance between the top of dissolved cavity and the overlying rock is 50m, and the maximum tensile stresses appeared at the central roof of the cavity, ($s_{tmax}$), is 1.18MPa.

With the development of dissolution, the cavity roof raises, and then $s_{tmax}$ raised. When the cavity top is near the roof rock (mud-conglomerate), tensile stresses appear not only at the top, but also at the rock salt below the overburden (mud-conglomerate). When the floor thickness is 15m, the maximum tensile tress at the cavity roof is 5.4MPa. Such a result is quite different from that of a cavity where no week rock on above of rock salt.

With the further decrease of the floor thickness, the values of tensile stress raised rapidly. When the floor thickness is 10m, the maximum tensile stress at the cavity top is as 7.38MPa, and the maximum tensile stress appeared at rock salt joining to overburden (mud-conglomerate) with a value of 6.06MPa (tension). When the floor thickness is 5m, the maximum tensile stress at the cavity top is 14.06MPa, and the maximum tensile stress appeared at rock salt joining to overburden is as high as 16.11MPa, as shown in Fig.3.

Fig.4 shows the contours of tensile stress where the stress values are greater than 1MPa. Test results in laboratory with rock samples show that the compressive and tensile strengths of the rock salt are respectively 4-12MPa and 0.5-2.5MPa [3]. Although there is hardly discontinuities exist in rock salt, the strength of rock mass should be smaller than that of rock samples. So failure is unavoidable with the upward of the dissolution until the floor thickness is less than 15m.

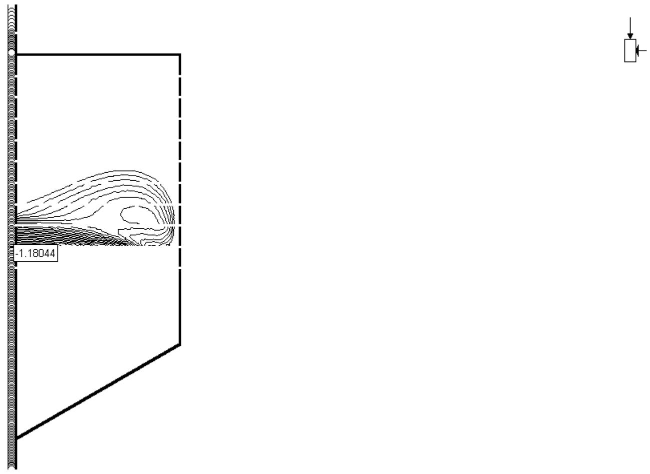



Fig.2 – Contours of tensile stresses (s $_3$) around the dissolved cavity when floor thickness is 50m (white colour outside the cavity represents the area of compressive stress)

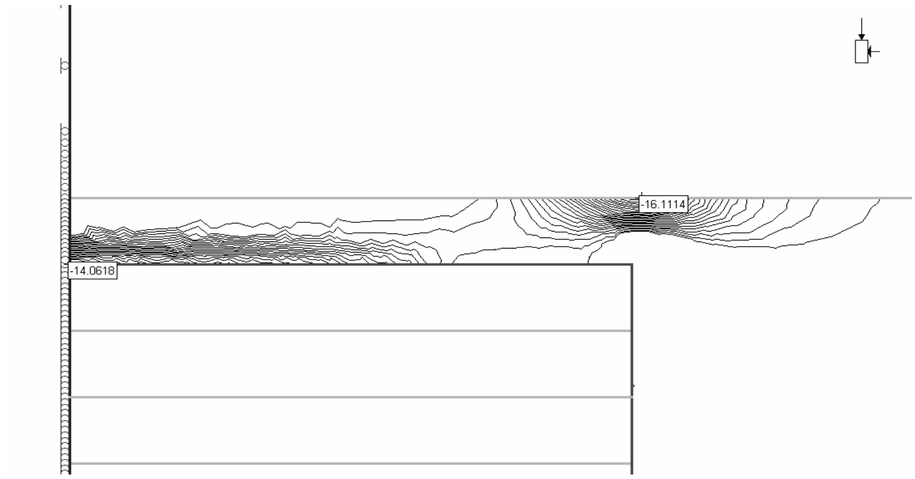



Fig.3 – Contours of tensile stresses around the dissolved cavity when floor thickness is 5m.

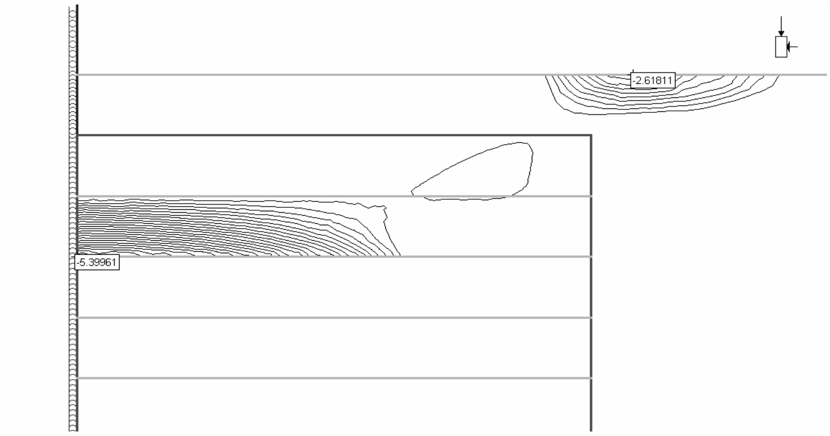



Fig.4 – Contours of tensile stresses around the dissolved cavity when floor thickness is 15m (contours shown the area where tensile stress values greater than 1MPa)

Fig.5 presented the relationship between the maximum tensile stress in the roof and the depth of the floor under the condition of diameter 77m obtained from the simulations. When the floor thickness (t) decreased from 60m to 30m, the maximum tensile stress ($s_{tmax}$) increased from 0.96MPa to 1.41MPa; when t is 20m, $s_{tmax}$ increased to 2.14MPa. When t is 10m, $s_{tmax}$ is as high as 4.38MPa; When t is 5m, $s_{tmax}$ is as high as 11.45MPa.

It should be noticed that tensile stress values below and next to the mud-conglomerate is independent of the maximum tensile stress at top of rock salt. When the “floor” thickness is greater than 25m, no tensile stress appeared there. When the “floor” thickness is 15m, the maximum value of tensile stress next to mud-conglomerate is 1.35MPa, about 50% of the maximum tensile stress appearing at the cavity roof. When the “floor” depth is 10m, the maximum value of tensile stress next to mud-conglomerate is 3.52MPa, about 20% lower than that appears at the cavity top. When the “floor” depth is 5m, the maximum value of tensile stress next to mud-conglomerate is 12.15MPa, about 6% greater than that appearing at the cavity roof. Obviously, the tensile stress appearing at the rock salt adjacent to mud-conglomerate will decrease the cavity stability very much when the “floor” thickness is thin enough.

Since the tensile strength of the samples of rock salt is usually less than 2MPa, failure is unavoidable when the “floor” thickness is less than 20m. With the raising of the cavity top, failure zone would develop continually and may produce a large circle, and causing collapse at last. The authors believe that this is the main reason that produced the accident of 1989.

Above results were obtained for the condition that the diameter of the drilling well is 77m. For the purpose to know the influences of the drilling diameter to stability of the cavities, more simulations were conducted. The results were presented in Fig.6. These results show that the drilling diameter has great influence on the tensile stresses appeared in the rock salt. For example, when the “floor” thickness is 5m, the maximum tensile stress at the cavity top is 2.68MPa for the condition of diameter 40m and is 7.82MPa as for the condition of diameter 50m.

For different cavity diameters, the safety floor thickness is quite different. For example, when the diameter is 40m and the floor thickness is 5m, the maximum tensile stress in the rock salt is 2.68MPa meaning that some part of the cavity may fail. However, the scope of the rock salt where tensile stresses exceed strength value is relatively small, so the cavity of the drilling well can keep stable although local failure may appear. When the diameter is 60m, failure would be more serious even when the floor thickness is 10m, because the maximum tensile stress at this moment is higher than the condition when the diameter is 40m and the floor thickness is 5m.

In the mine exploitation, diameter of the drilling well is very important. From the consideration of economy, larger value of diameter is better, since it would promote higher recovery and produce better benefits. However, larger diameter also means lower safety factor of the cavity. To improve the safety factor, the “floor” should have enough thickness, or else accidents like what happened at drilling well No.12 are unavoidable.

To keep balance between safety and economy, the minimum floor thickness should be different when the cavity diameter is different. It is suggested to considering the results shown in Figs 5 and 6 in the following drilling well design.

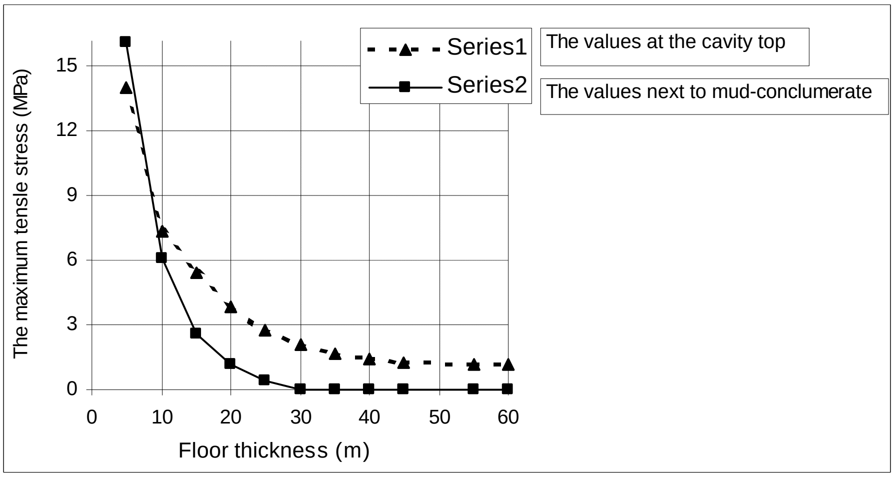



Fig. 5 – The maximum tensile stress in the roof vs. floor thickness when the cavity diameter is 77m.

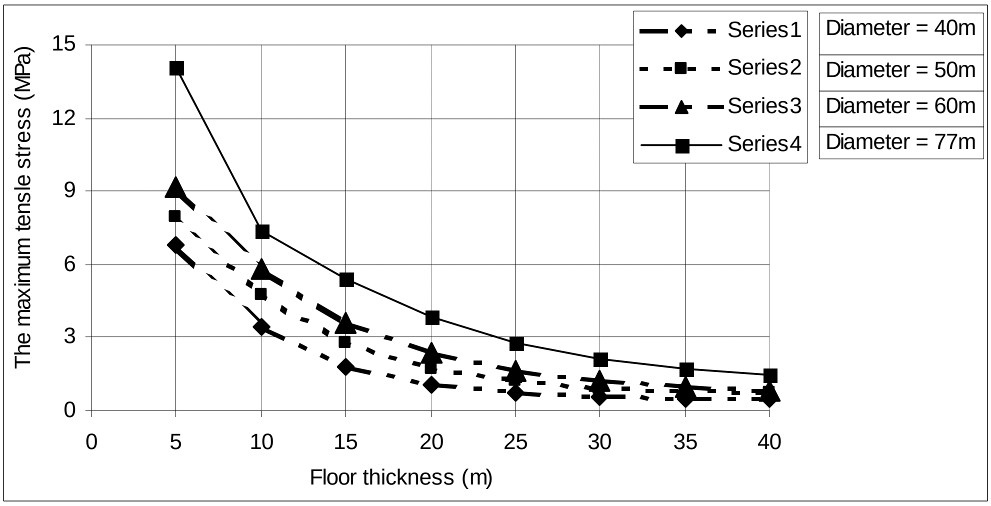



Fig.6 – Floor thickness vs. the maximum tensile stresses in the rock

It is well known that rock salt is a rock type that has typical behaviour of rheology, i.e., the deformation is connected with time. In Qiaohou salt mine, measurement results from underground openings has shown that rheology deformation does exist [2]. Since the excavation of a drilling well continues usually several years, rheology behaviour will influence the stress distribution and the stability of the drilling cavities. Test results with the samples of rock salt of this mine also shown that non-linear stage exists on the stress-strain curves with the raising of stress values, where the slope of the curve is much smaller than the initial linear stage. Unfortunately, no test results on rheology behaviour are available and the related analyses cannot be conducted. The results of this paper are then some primary ones.

## 4. CONCLUSIONS

(a) Tensile stress appeared in the cavity top was the main reason of making the cavities' failure and collapse.

(b) The thickness of the “floor”, or the vertical distance between the cavity top and the overlying rock (mud-conglomerate), and the cavity diameter are the main factors of influencing the tensile stress values. With the decrease of the “floor” thickness and increase of the diameter, the values of tensile stresses increase rapidly.

(c) For a drilling well of which the diameter is as high as 77m, like drilling well No.12, the “floor” thickness should be larger than 15m or else collapse is unavoidable.

## REFERENCES

[1] Kaiser, P.K., Yazici, S. and Maloney, S., Mining-induced stress change and consequence of stress pass on excavation stability – a case study. *Int. J. Rock Mech. Min. Sci*., **38**, pp167-180 (2001).

[2] Yu Xianbin, Yang Jincan, Li Hanxuan, Deformation survey of underground openings and the data analysis of Qiaohou salt mine (in Chinese), *Journal of Kunming Institute of Technology,* No.5, 1994.

[3] Hong Bennian, Investigation report on engineering geology of Qiaohou salt mine (in Chinese), Kunming University of Science and Technology, 1991.

[4] Nguyen-Minh D., A method for the evaluation of the long term convergence of underground excavation in rocksalt. Rock Mechanics as a Multidisciplinary Science of the 32nd U.S. Symposium, The university of Oklahoma/Norman/10-12 June 1991, Jean-Claude Roegiers (Ed.), A.A. Balkema/Rottedam/Brookfield/1991.