

# EFFECTS OF SHALLOW SALT CAVITY ON SUBSIDENCE PROFILES UNDER SUPER-CRITICAL CONDITION

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## **Abstract**

Physical model tests were performed to study surface subsidence under various widths and heights of shallow salt cavity induced at the boundary of salt bed and overlying soil stratum. Uniform spherical acrylonitrile butadiene styrene plastic (ABS) balls with 6 mm diameter were used to form particulate medium of the overburden. Width and depth of settlement trough under different geometries and depths of salt cavity were measured by 3-D laser scanner. PFC code was used to correlate the subsidence components with cavity geometries. Results show that depth of surface settlement is mainly controlled by cavity height, while the extent of settlement area is governed by cavity width. Results from discrete element analyses agree reasonably with those of physical model. Sets of empirical equations were developed to correlate the test measurements with the numerical results. They are applicable for predicting cavity height and width based on the configurations of settlement trough and friction angles of overburden.

**Keywords:** Subsidence, physical model, settlement, salt cavity, friction angle

## **Introduction**

Rock salt in Maha Sarakham formation, northeast of Thailand has long been extracted by brine pumping method. The brine pumping technique has been applied where salt beds are relatively shallow (less than 100 m.), close to the edge of salt basin and mostly overlaid by

silty and sandy soils (Figure 1). Detailed geology and origin of Maha Sarakham salt is described by Warren (1999). The groundwater is high during rainy season. Brine (saline groundwater) is pumped up through borehole and left evaporated on the surface. This activity

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creates shallow salt cavities underneath, and subsequently induces uncontrollable surface subsidence (Wannakao *et al.*, 2005). The depression area and sinkhole or pot-hole (Lokhande *et al.*, 2014) are caused by deformation and failure of the cavity roof. The failure propagates upward through the overlying soil and reaches the ground surface (Figure 2). This occurs during dry season when the salt cavities lose internal support from groundwater. This ground movement is classified as super-critical subsidence.

For sub-critical subsidence, the deformation of the overburden is largely in elastic mode. The width and height of the cavity can be back-estimated from the depth and extent of the subsidence trough. The correlations can be made by numerical modelling (e.g., Sartkaew *et al.*, 2018) or by profile functions as proposed by Singh (1992).

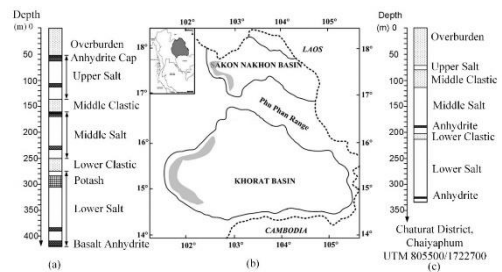
For super-critical condition, failure and movement of the overburden into the cavity below are the main factors controlling the characteristics of the subsidence trough. Prediction of these phenomena requires numerical analysis or scale-down physical model simulation. Thongprapha *et al.* (2015) and Saoanunt *et al.* (2018) performed physical model tests in an attempt to predict the width and height of the salt mine openings from the subsidence trough characteristics in the Maha Sarakham formation. They used gravel and fine-grained sand to simulate the overburden material. High intrinsic variability of their test results occurred. The uncertainties arise when they try to extrapolate their physical model results toward large scales under in-situ condition. This is in part due to the inconsistency of the angularity and roundness of the tested sand and gravel particles which are difficult to control even under laboratory condition.

The primary goal of this study is to correlate the geometry of shallow salt cavity with the subsidence trough configurations. The physical model test and numerical simulations are performed. Spherical acrylonitrile butadiene styrene (ABS) plastic balls are used to simulate particulate material of the overburden. This is to obtain a more

consistency of the test results, as compared to the previous studies. Discrete element analyses with PFC program are performed to compare with the physical model results. Mathematical relationships between subsidence characteristics and the cavity geometry are developed.

## Testing Material

The ABS balls with nominal diameters of 6 mm were used to represent soil overburden. Attempts have been made to seek particles that are uniformly produced, smooth and perfectly spherical shape. Several materials had been considered, including plastic beads, ground rock gravels, foam balls, glass marbles, and wooden balls. ABS ball turns out to be the best candidate. Direct shear test was performed to determine the frictional properties of the ABS mass in accordance with the ASTM D3080/D3080M standard practice. The bulk density of ABS balls is  $582 \text{ kg/m}^3$ . The friction angle



**Figure 1.** Typical geologic sequence of Maha Sarakham formation (a), shaded areas are where brine pumping has been practiced (b), and example of borehole logging near edges of basins (c)



**Figure 2.** Sinkholes caused by brine pumping in Sakon Nakhon province, northeast of Thailand (Wannakao *et al.*, 2005)

is 15 degrees. The cohesion is effectively zero. The normal ( $K_n$ ) and shear ( $K_s$ ) stiffness are 20 GPa/m and 1 GPa/m. They are determined from the linear portion of the shear-normal stress curves.

### Testing Apparatus and Method

The physical model test here uses a trap door apparatus developed by Thongprapha *et al.* (2015). It consists of three main components: material container, cavity simulator, and surface measurement system. The testing space of the container is  $0.75 \times 0.25 \times 0.30 \text{ m}^3$ . The cavity simulator is formed by array of plastic blocks ( $30 \times 250 \text{ mm}^2$  wide and 120 mm high) placed underneath the container. Combination of these blocks can represent various widths and heights of the cavity. For this study, the cavity width ( $W$ ) was taken from 30 mm to 120 mm. The length was maintained at 250 mm. The cavity height ( $H$ )

was simulated from 30, 60, 90, to 120 mm. The cavity depth ( $Z$ ) was simulated between 120 and 300 mm with 30 mm increment. Laser scanner with a precision of  $\pm 0.001 \text{ mm}$  mounted on X-Y sliding rails was used to measure top profile of the tested material (Figure 3). The test parameters and variables used in the simulations are shown in Figure 4.

Testing is started by filling the sample container with ABS balls to a pre-defined thickness which represents cavity depth. The mass of ABS balls was lightly packed, and the top surface was flattened before measurement. The cavity was simulated by pulling down the plastic blocks under the container. The balls flowed into the cavity, and subsequently settlement of the top surface was induced. The laser scanner measures the surface profile before and after the settlement occurred. The measurement interval is 1 mm. The vertical measurements were read to the nearest 0.1 mm. Each cavity configuration was performed three times to obtain repeatability of the results.

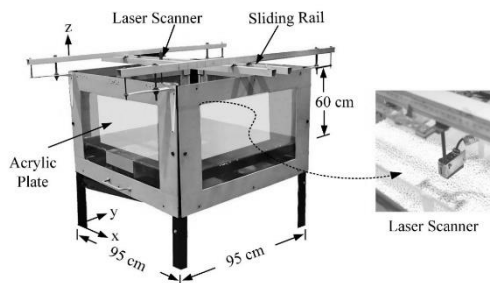


Figure 3. Trap door apparatus (Thongprapha *et al.*, 2015)

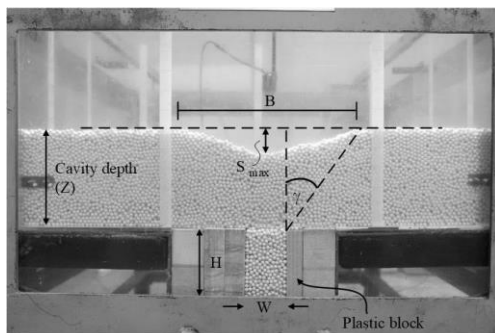


Figure 4. ABS balls in sample container of trap door apparatus and variables used in physical modeling

### Test Results

Some results from the physical model tests are given in Figure 5. The figure presents the subsidence profiles from the center to the edge of the induced trough for various cavity heights and widths. For all cases, the largest surface settlement is induced at the center of the trough. Under the same cavity geometry,

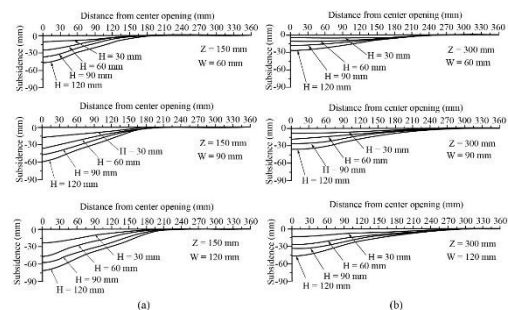
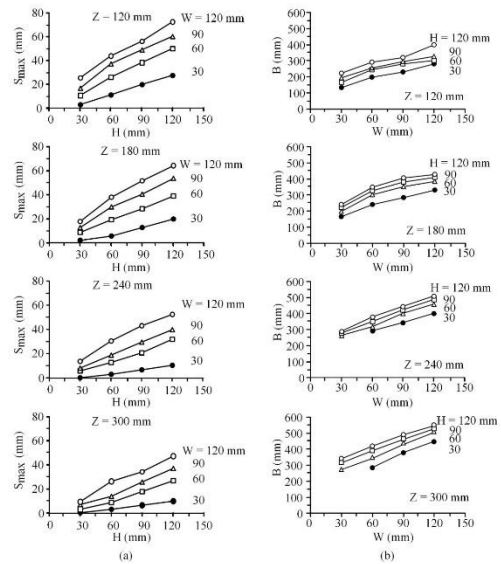


Figure 5. Subsidence profiles from different opening widths and height, for depths of 150 mm (a) and 300 mm (b)

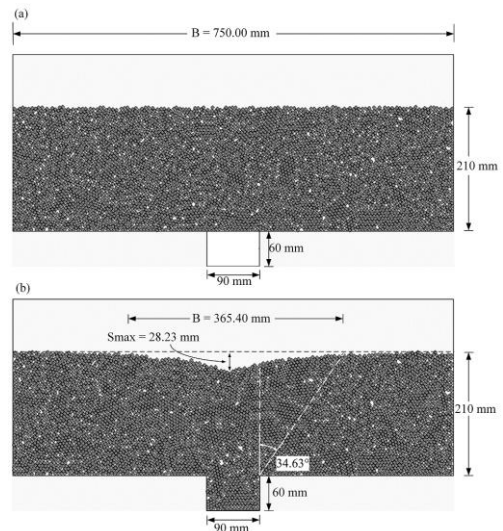
deep cavities showed shallower and wider trough than the shallower ones. As the cavity height increases, the maximum subsidence increases. This holds true for all simulated depths. Maximum subsidence ( $S_{\max}$ ) in terms of cavity height ( $H$ ) are shown in Figure 6(a). Trough width ( $B$ ) as a function of cavity width ( $W$ ) are given in Figure 6(b). The results suggest that depth and width of subsidence trough increased with cavity height and width. This is because under super-critical condition, the ABS balls can collapse (flow) into the cavity more easily, and hence induced deeper and wider subsidence trough. The trough depth decreased as the cavity depth ( $Z$ ) increased. This is probably due to the inter-locking of the ABS balls above the cavity. This observation agrees with those reported by Bhasin and Hong (1998), Kim and Ha (2014) and He and Xu (2018) who conclude that the maximum subsidence tends to be sensitive to the cavity height only for the wide cavities at shallow depth. The trough depth is not sensitive to the height of deep cavities.

## Numerical Simulations

Discrete element analyses using PFC<sup>2D</sup> (Itasca, 2008) were performed to verify the correctness of the physical model results, and to extrapolate the numerical results beyond the range of the test parameters toward the in-situ condition. The analysis was made under plane strain condition. The geometric and loading boundary conditions defined in the analyses were identical to those used in the physical models. The parameters and variables used in the numerical simulations were also identical to those of the physical model tests. After the particles in the model were at rest (e.g. Figure 7(a)), the wall above the cavity was deleted to simulate the cavity under different shapes. The particles continuously flowed into the cavity until filled, and subsequently the surface settlement was formed (Figure 7(b)). The simulation was terminated after the model reached equilibrium (movement of simulated particles no longer occurred).



**Figure 6. Examples of maximum subsidence as a function of opening height (a), and trough width as a function of cavity width (b)**



**Figure 7. Example of PFC2D model for surface subsidence. Before (a) and after (b) cavity is created**

The physical model results are compared with those of the numerical simulations, for some cases in Figure 8. They are presented in terms of the maximum subsidence as a function of cavity height and trough width. The numerical simulations agree reasonably well with those observed from the physical model. Some discrepancies may be due to the fact that the numerical calculation is based on perfect spheres of rigid particles, while the physical simulations exhibit some intrinsic variability of the ABS balls. This explains why the numerical results show slightly greater  $S_{max}$  and  $B$  values than those of the physical model tests.

## Mathematical Relationships

Mathematical relationships between the subsidence components and the cavity geometrics are derived. The cavity height ( $H$ ), width ( $W$ ), depth ( $Z$ ), trough width ( $B$ ) and maximum subsidence ( $S_{max}$ ) were first equivalated by size of the ABS ball ( $B_s$ ). The equivalent cavity height ( $H_e$ ), width ( $W_e$ ) and depth ( $Z_e$ ), and trough depth ( $S_e$ ) and width ( $B_e$ ) are defined as:

$$H_e = H/B_s \quad (5)$$

$$W_e = W/B_s \quad (6)$$

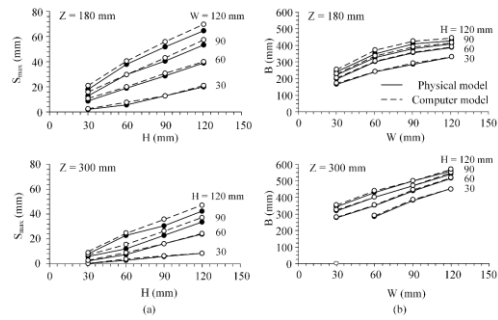
$$S_e = S_{max}/B_s \quad (7)$$

$$B_e = B/B_s \quad (8)$$

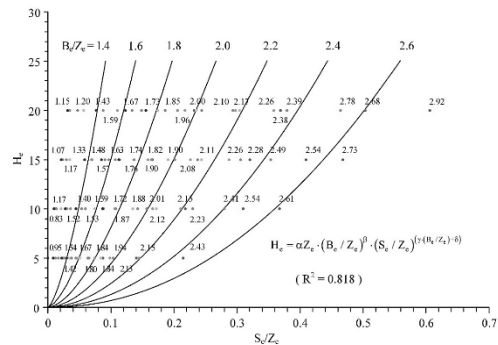
$$Z_e = Z/B_s \quad (9)$$

where  $B_s$  is particle size of ABS balls with nominal diameters of 6 mm.

This is primarily to isolate the particle size effect, and hence allows extrapolating the modeling results to the actual in-situ condition where the cavity sizes are different from those used in the physical modeling. Similar technique has been used by Saoanunt *et al.* (2018). The changes of equivalent height ( $H_e$ ) as a function of equivalent subsidence which was normalized by equivalent cavity depth ( $S_e/Z_e$ ) are shown in Figure 9. A power equation is proposed to represent their relation, as follows:



**Figure 8.** Comparisons between physical model (solid lines) and Numerical (dash lines) simulation results for depths of 180 and 300 mm. (a)  $S_{max}$  as a function of cavity height, and (b) trough width as a function of cavity width



**Figure 9.** Curve fits for equivalent cavity height ( $H_e$ ) as a function of normalized subsidence ( $S_e/Z_e$ ). Numbers in diagram represent normalized trough width ( $B_e/Z_e$ )

$$H_e = A \cdot (S_e/Z_e)^B \quad (10)$$

where  $A$  and  $B$  are empirical constants. Regression analyses using SPSS statistical software (Colin and Paul, 2012) were performed to determine these constants. The constant  $A$  represents the ultimate slope of the  $H_e$ - $S_e/Z_e$  relations while  $B$  defines their curvatures. The diagrams in Figure 9 are only sensitive to constant  $B$  when  $H_e$  is low (less than 5). It was found that the  $A$  and  $B$  values

could be defined in terms of cavity depth and trough width, as follows:

$$A = \alpha Z_e \cdot (B_e/Z_e)^\beta \quad (11)$$

$$B = \gamma \cdot (B_e/Z_e) + \delta \quad (12)$$

where  $\alpha$ ,  $\beta$ ,  $\gamma$ , and  $\delta$  are empirical constants equal to 32.16, -2.13, 0.53, and 0.69 respectively. Good correlation is obtained ( $R^2 > 0.8$ ). Since the constant B is related to the variation of  $H_e$ - $S_e/Z_e$  relation, the constants  $\gamma$  and  $\delta$  would likely depend on the friction angle of the simulated overburden material.

To verify whether the constants  $\gamma$  and  $\delta$ , depend on the overburden friction angles, additional PFC analyses were carried out with the overburden friction angles varying from 15, 20, 25, 30, to 35 degrees (Figure 10). The cohesion is taken as 0 to represent cohesionless material of the actual top soil in the brine pumping area. It is found that the empirical constants  $\gamma$  and  $\delta$  are clearly dependent of the friction angle ( $\phi$ , degrees), which can be described by linear equations as:

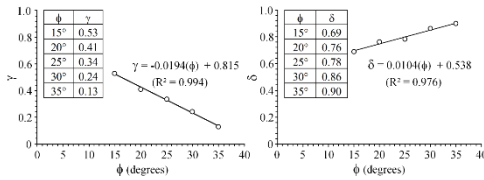


Figure 10. Parameters  $\gamma$  and  $\delta$  as a function of friction angle

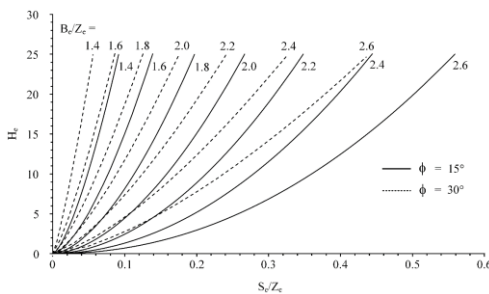


Figure 11. Equivalent cavity height ( $H_e$ ) as a function of normalized maximum subsidence ( $S_e/Z_e$ ) for friction angles of 15 and 30 degrees

$$g = -0.0194(f) + 0.815 \text{ (degrees)} \quad (13)$$

$$d = 0.0104(f) + 0.538 \text{ (degrees)} \quad (14)$$

Figure 11 gives the equivalent cavity height in terms of the maximum subsidence for friction angles ( $\phi$ ) = 15 and 30 degrees. The coefficients of correlation are greater than 0.9. The diagram in Figure 11 shows that under the same cavity height, higher friction angle of the overburden will result in a lower maximum subsidence on the ground surface. This agrees with the conclusion drawn by Thongprapha *et al.* (2015). Figure 12 shows the equivalent cavity width ( $W_e$ ) as a function of trough width normalized by the cavity depth ( $B_e/Z_e$ ). Similar to the equivalent cavity height above, an empirical equation was proposed to describe the cavity width under different normalized subsidence magnitudes, as follows:

$$W_e = C \cdot (B_e/Z_e)^D \quad (15)$$

$$C = \eta Z_e \cdot (S_e/Z_e)^\kappa \quad (16)$$

$$D = \lambda \cdot \ln(S_e/Z_e) + v \quad (17)$$

where  $\eta$ ,  $\kappa$ ,  $\lambda$  and  $v$  are empirical constants, equal to .01, -0.52, -0.19, and 3.45, respectively. The proposed equation can be applied only for large  $W_e$  values (overburden particles are much smaller than cavity width). This limitation is defined by a dash line in Figure 10. Large particles in the overburden compared to the cavity width may not flow freely into the cavity, and hence bridging of the particles may occur above the cavity. The

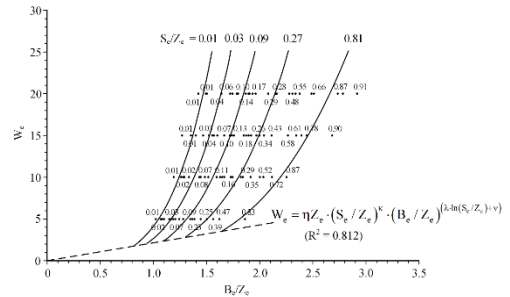


Figure 12. Curve fits for equivalent cavity width ( $W_e$ ) as a function of normalized trough width ( $B_e/Z_e$ ). Numbers in diagram represent normalized subsidence ( $S_e/Z_e$ )

friction angle of the overburden would affect the trough width only when the equivalent cavity width ( $W_e$ ) is small. Since the proposed equations (15) through (17) are applicable for large  $W_e$  (above dash line limitation – Figure 12), the diagrams in the figure tend to be independent of the overburden friction angle. This postulation agrees with those of Singh (1992) that under super-critical condition,  $B_e$  is mainly governed by  $W_e$ , not by the overburden properties.

## Discussions and Conclusions

Both physical models and numerical simulations suggest that for a shallow cavity overlain by cohesionless materials, the maximum subsidence closely relates to the cavity height, while the cavity width controls the trough width. For very narrow cavities at great depths, the  $S_{max}$  is insensitive to height of the cavity. Shallow salt cavity induces deeper and narrower trough, as compared to the deeper ones. The trough width however is highly sensitive to the cavity depth. This observation complies with the conclusion drawn by Singh (1992) that under super-critical subsidence condition, the maximum subsidence remains constant, while the extent of the settlement area increases with cavity width. Equations in Figures 9 and 12 can be used to predict equivalent cavity height ( $H_e$ ) and width ( $W_e$ ), primarily because  $H_e$  is mainly governed by  $S_{max}$ , while  $W_e$  is controlled by trough width ( $B$ ), as suggested by the physical model and numerical results. The proposed  $W_e$ - $B_e$ / $Z_e$  relation is in a power form which can represent the actual condition more closely, as compared to the linear relation proposed by Saoanunt *et al.* (2018). In addition, it provides a good transition to the limit condition under low  $W_e$ , as indicated by a dash line in Figure 12. The numerical simulation under the lowest  $W_e$  value of 5 ( $W = 30$  mm,  $B_s = 6$  mm) with  $B_e/Z_e = 1.0$  shows satisfactory results – no bridging has been observed. This suggests that equation (15) is sufficiently reliable toward this limit. Below this limit, the equation remains questionable. However, for predicting

actual salt cavity overlain by silty-sand larger, the  $W_e$  and  $B_e$  values are significantly larger than those used in the physical and numerical simulations.

The effect of particle size has not been studied here. The equivalent  $S_{max}$  obtained in our study agree reasonably well with those obtained by Saoanunt *et al.* (2019) who use sand particle with nominal sizes of 2 mm. Some discrepancies remain. The  $H_e$  and  $W_e$  values predicted by Saoanunt *et al.* (2019) are slightly lower than those given by equations (10) and (15) here. This is due to the fact that their tested sand mass has cohesion of 15 kPa which has been incorporated into their analysis, while our ABS ball mass has zero cohesion.

The proposed equations may be used as a predictive tool to estimate the height and width of shallow cavity, based on the subsidence extent and depth, and the friction angle of overburden materials. These equations may be applicable for other areas with similar geologic conditions used here (e.g. cohesionless overburden such as sand, silt and gravel). To apply these equations, the particle sizes of the overburden and cavity depth are required, which can be obtained from field investigation.

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