A Theoretical Consideration and Numerical Analysis for Volumetric Expansion Ratio of Rock Mass

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1. Introduction

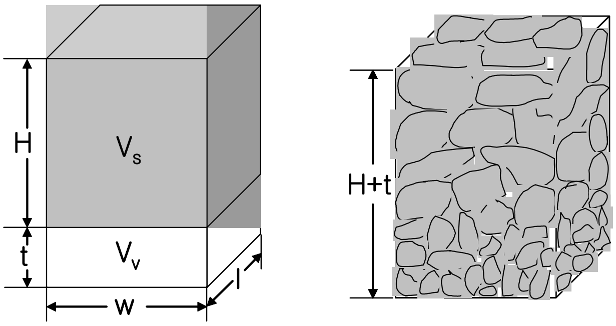
The volumetric expansion ratio of rock mass on the subsidence occurrence area can explain why the depth of the surface subsidence is lower than the height of an opening; it is because the empty space of the gangway is filled with the broken rock. But, until now, the volumetric expansion ratio of rock mass has been calculated by the theoretical equation through numerical models, and it has hardly been used in the studies of the subsidence prediction and the restoring plan. Also, the studies of the surface subsidence that did not consider the volumetric expansion ratio have overestimated the surface subsidence to some degree.

Therefore, in this study, The authors researched a theoretical consideration about calculating the volumetric expansion ratio of rock mass. And, unlike existing continuum analysis, the numerical analysis was conducted by discontinuum modeling using UDEC(universal distinct element code) in order to analyze the subsidence mechanism quantitatively.

2. Theoretical consideration about calculating the volumetric expansion ratio of rock mass

In case that roof failure begins by the dimension of the gangway, the collapse of roof can move upward and stop when the rock layer is strong enough or the empty space of the gangway is filled with broken rocks. The volumetric expansion ratio of broken rocks varies according to the strength of roof, the depth of the gangway, and the dimension of the gangway, but when subsidence moves from the gangway to the surface a calculation, considering both the subsidence influence zone and the subsidence amounts according to the subsidence type, is needed.

The volumetric expansion ratio can be defined theoretically through the relation between the initial volume before a collapse and the final volume after a collapse as in Fig. 1. To calculate the height of the collapse with the height of opening and the variation of the volumetric expansion ratio, the relation between the volumetric expansion ratio and the height of the collapse is suggested simplifying various stacking patterns of broken rocks by the difference of the collapsed shape as in Fig 2(B.C. Kim et al., 2001).



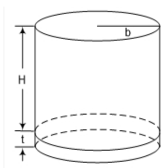
(a) Before the collapse (b) After the collapse

Fig. 1. Schematic diagram of volumetric expansion ratio model for square column (H: height of overburden to be collapsed, t: height of an opening, w: width of an opening, l: length of an opening)

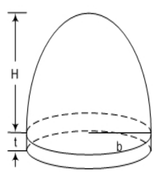
$$B = \frac{V_f - V_i}{V_i} = \frac{(V_s + V_v) - V_s}{V_s} = \frac{V_v}{V_s} \tag{1}$$

where B is the volumetric expansion ratio, V_f is the final volume after a collapse, V_i is the initial volume before a collapse, V_v is the volume of an opening, and V_s is the volume of an overburden to be collapsed.

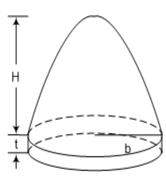
$H = \frac{t}{B}$



$H = 1.5\frac{t}{B}$



$H = 2\frac{t}{B}$



$H = 3\frac{t}{B}$

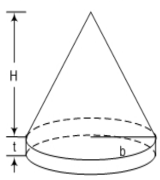


Fig. 2. Relationship between volumetric expansion ratio and height of overburden to be collapsed with variation of collapsed shape (H: height of overburden to be collapsed, t: height of an opening, B: volumetric expansion ratio)

Fig. 2 shows theoretical model about sinkhole subsidence for calculating the height of the collapse through the volume expansion ratio of being collapsed rock mass in the constant volume of the gangway. Although the height of the collapse can vary by the volumetric expansion ratio of rock types, and because it can vary according to in-situ condition such as constituents of overburden rock and the surface of discontinuity, it is difficult to calculate the exact value. As a result, even though the analysis of the volume expansion ratio of each rock consisting subsidence occurrence area is important, because the overall volume expansion ratio varies according to in-situ condition the analysis of the entire subsidence occurrence area, considering the subsidence influence zone and the subsidence amounts, is needed.

If sinkhole subsidence analyzed by previous theoretical research has a constant area as in Fig. 3 and the roof collapse can reach to the ground surface with the constant area, like Eq.(2) the surface subsidence can be simply calculated through the height of an opening, the depth, and the volumetric expansion ratio.

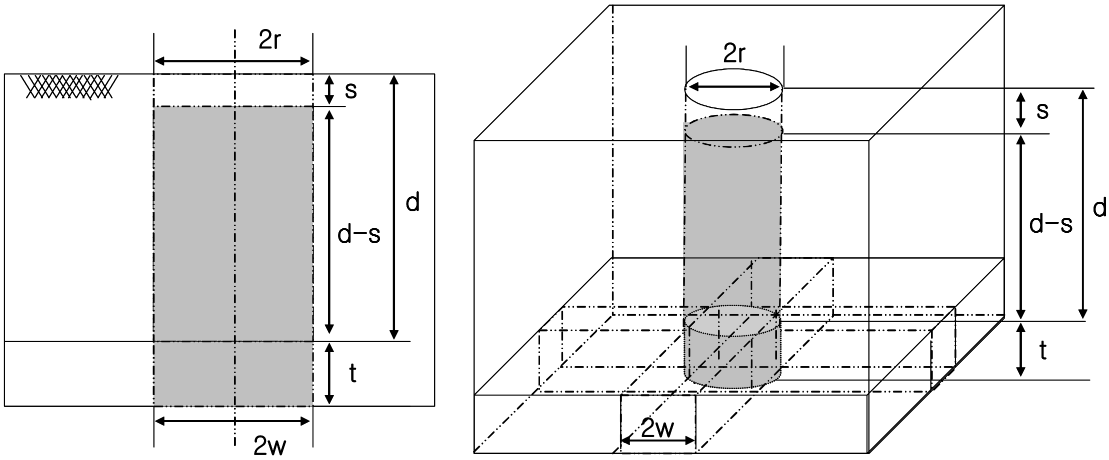


Fig. 3. Schematic diagram of volumetric expansion ratio model for sinkhole subsidence
(d: depth from the surface to the gangway, t: height of an opening, w: the radius of the gangway, r: radius of the subsidence influence, s: subsidence)

$$B = \frac{V_f - V_i}{V_i} = \frac{A(d-s) + At - Ad}{Ad} = \frac{t-s}{d}, \qquad s = t - dB \tag{2}$$

Where B is the volumetric expansion ratio, V_f is the final volume after a collapse, V_i is the initial volume before a collapse, A is an area of the subsidence, d is the depth from the surface to the gangway, s is the depth of the subsidence, and t is the height of an opening.

Because the trough subsidence has broader radius of subsidence influence than the width of the gangway and the more it moves from the gangway to the surface, the more the subsidence area increases, the volume of overburden to be collapsed increases. When analyzing the maximum volume expansion ratio by way of simplifying the shape of the trough subsidence, the volumetric expansion ratio can be defined as in Eq.(3)~(8), if the subsidence occurs in the shape of circular truncated cone from upper part of the gangway to the surface, as in Fig. 4. These equations is applicable not only to the trough subsidence but the sinkhole subsidence(when w≠r).

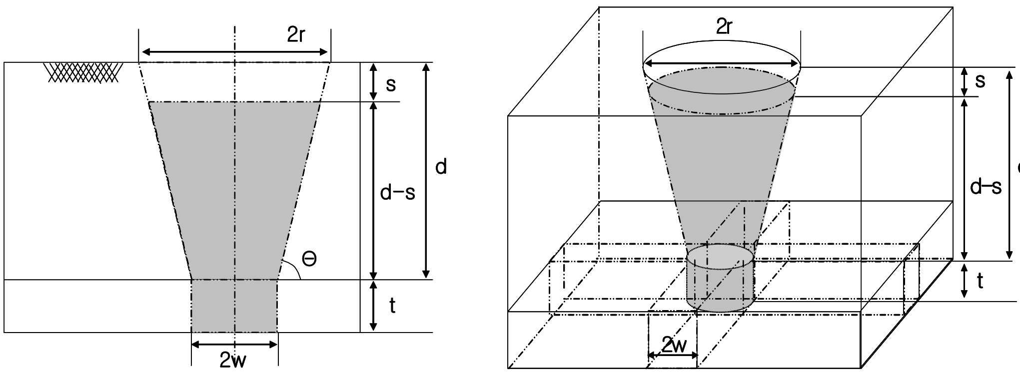


Fig. 4. Schematic diagram of volumetric expansion ratio model for trough subsidence
(d: depth from the surface to the gangway, t: height of an opening, w: the radius of the gangway, r: radius of the subsidence influence, θ: the angle between the upper part of the gangway and the surface end part of subsidence, s: subsidence)

$$r = w - d\cot\theta \tag{3}$$

$$\theta = \tan^{-1}\left(\frac{-d}{r-w}\right) \tag{4}$$

$$V_i = -\frac{\pi}{3\tan^2\theta} d\left\{(d)^2 + 3r\tan\theta(d + r\tan\theta)\right\} \tag{5}$$

$$V_f = \frac{\pi}{3\tan^2\theta}(s-d)\left\{(s-d)^2 + 3(s + r\tan\theta)(d + r\tan\theta)\right\} + \pi t w^2 \tag{6}$$

$$B = -\frac{(s-d)\left\{(s-d)^2 + 3(s + r\tan\theta)(d + r\tan\theta)\right\} + 3tw^2\tan^2\theta}{d\left\{d^2 + 3r\tan\theta(d + r\tan\theta)\right\}} - 1 \tag{7}$$

$$s = -\sqrt[3]{Bd\left\{d^2 + 3r\tan\theta(d + r\tan\theta)\right\} - (r\tan\theta)^3 + 3tw^2\tan^2\theta} - r\tan\theta \tag{8}$$

Where r is the radius of the subsidence influence, w is the radius of the gangway, d is the depth of the gangway, θ is the angle between the upper part of the gangway and the surface end part of subsidence, V_i is the initial volume before a collapse, V_f is the final volume after a collapse, t is the height of an opening, B is the volumetric expansion ratio, and s is the subsidence(when $d<0$, $s<0$, $w \neq r$).

When the depth of the subsidence is 0m, the volumetric expansion ratio for the gangway having the certain depth and dimension is the maximum volumetric expansion ratio for the volume of overburden to be collapsed. For example, when the depth of the subsidence is 0m, the width is 10m, the height of the gangway is 8m, and the depth of the gangway is -20m, the possible variation of the maximum volume expansion ratio according to the variation of radius of subsidence influence is as in Fig. 5. As the radius of subsidence influence increases, both the initial volume before a collapse(V_i) and the final volume after a collapse(V_f) are increases, but the maximum volume expansion ratio(B) tends to be decreased gradually because the volume of the gangway(V_o) is constant. Likewise, when the depth of the subsidence is 0.8m, it seems to be a similar inclination, but the maximum volume expansion ratio(B) having the subsidence of 0.8m is close to 0 as the final volume after a collapse(V_f) and the initial volume before a collapse(V_i) are the same gradually(Fig. 6).

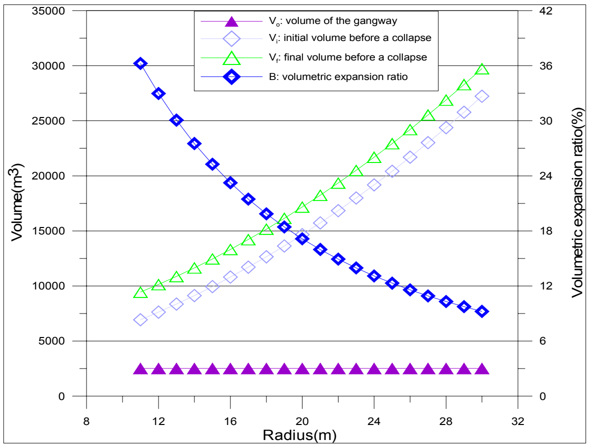


Fig. 5. Relationship between volume and volumetric expansion ratio according to radius at s=0(d=-20m, w=10m, t=8m)

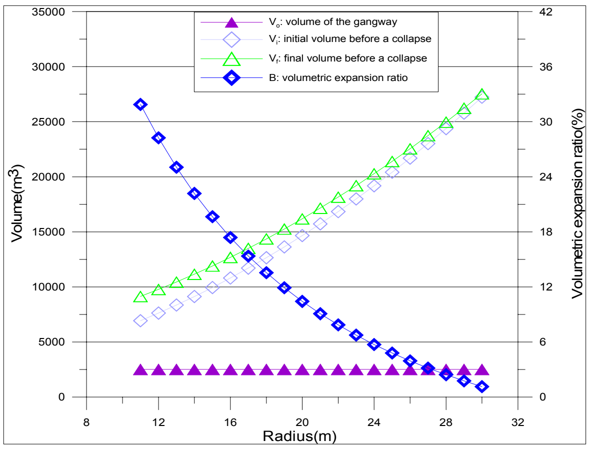


Fig. 6. Relationship between volume and volumetric expansion ratio according to radius at s=-0.8(d=-20m, w=10m, t=8m)

Also, if the certain dimension of the gangway(w=10m, t=8m) has the certain radius of subsidence influence(r=20m), the variation of the maximum volume expansion ratio according to the increase of the depth is the same as Fig. 7(s=-0m), and Fig. 8(s=-0.8).

When the subsidence of 0.8m occurs, the variation of the final volume after a collapse of Fig. 6, and Fig. 8 differs according to the difference between the increase of the radius and depth. As a result, the maximum volumetric expansion ratio of trough subsidence about the gangway having a certain volume is influenced largely by the variation of volume according the radius than that of the depth.

The surface subsidence by the gangway can analyze the variation of the maximum volume expansion ratio according to theoretically limited volume of the gangway, the variation of both the radius of subsidence influence and the depth of the gangway. Considering this, if the volume expansion ratio suited for in-situ condition is applied, both the subsidence influence zone and the subsidence amounts can be predicted more precisely.

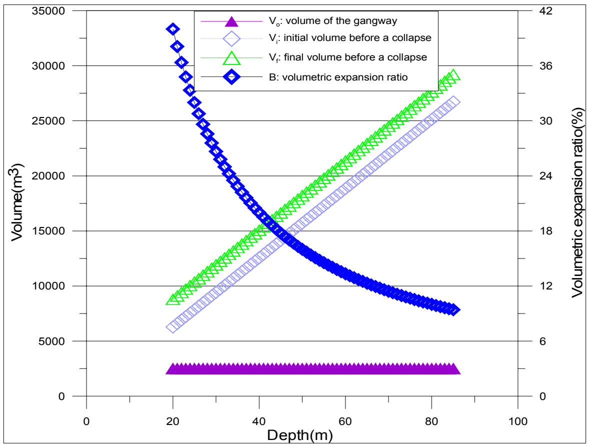


Fig. 7. Relationship between volume and volumetric expansion ratio according to depth at s=0.0(r=20m, w=10m, t=8m)

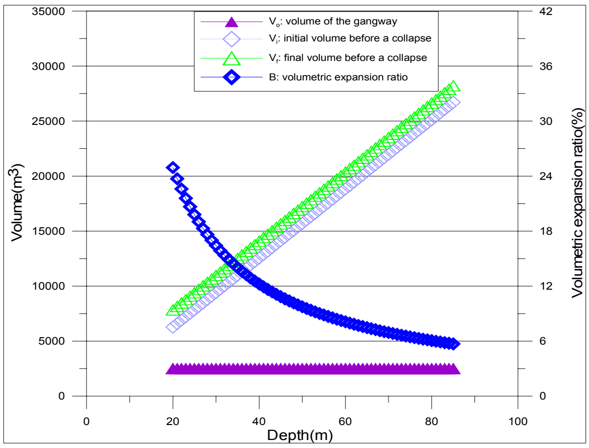


Fig. 8. Relationship between volume and volumetric expansion ratio according to depth at s=-0.8(r=20m, w=10m, t=8m)

3. Numerical Analysis

Because most of the domestic ground subsidence has applied mining methods such as slant shute block caving and sublevel caving to an irregular coal bed of the steep, the subsidence influence zone on the ground is relatively confined to a narrow influence zone. But, once the subsidence occurs, it results in a large amount of subsidence and the shape of irregular sinkhole subsidence in subsidence curve. In this study, a discrete element program, or UDEC(Universal Distinct Element Code), is used to access through numerical model by discontinuum model.

An analysis model makes a vertical and horizontal joint crossing at right angles each other and simplifies it to a square. Because the volume of the void generated by being collapsed block influences the volumetric expansion ratio, in order to analyze it elastic analysis is used not to cause transformation of the block to occur. In addition, because the process such as collapse or separation should occur on the underground in advance to generate the subsidence by the gangway, a low value is applied to emerging joints.

3.1 Behavior of subsidence according to variation of horizontal to vertical stress ratio(K)

The ground subsidence occurs due to the decline of the strength in the overburden rock weathered by the effect of underground water as time goes by and the stress is redistributed at the same time. At this moment, because the horizontal stress around the gangway is changed by disturbance of the ground if the vertical stress by overburden is constant, in order to analyze the behavior of block, the input data of joint is lowered and K is varied. The depth of the gangway is 25m, the height of the gangway is 2m, the width is 6m, and the block size is 0.5m are maintained as in Fig. 9, and K is changed to 1.5, 1.0, 0.8, and 0.6. Input data is Table 1, 2.

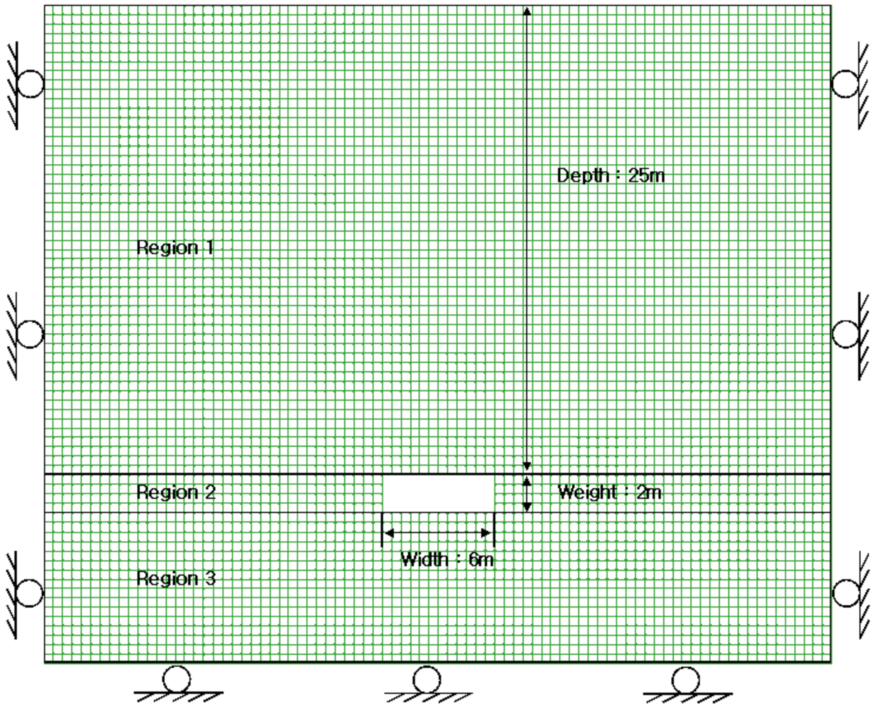


Fig. 9. Model for K-ratio analysis(42×35m)

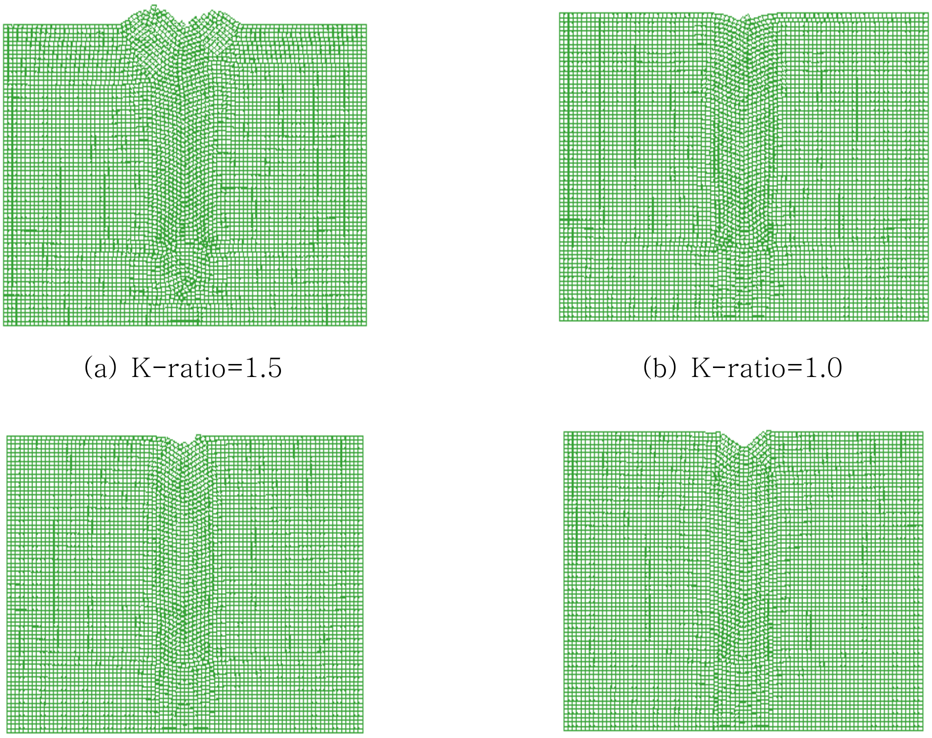
Table 1. Input data of joint property for K-ratio analysis

	Normal stiffness (MPa/m)	Shear stiffness (MPa/m)	Cohesion (MPa)	Friction angle (°)
Region 1	15	35	0.030	7.2
Region 2	20	40	0.040	5.6
Region 3	25	45	0.060	8.0

Table 2. Input data of rock mass property

	Density(kg/m^3)	Young's modulus(MPa)	Poisson's ratio
Region 1	2000	62,000	0.29
Region 2		56,000	0.28
Region 3		67,000	0.28

As a result of the analysis, normal sinkhole subsidence occurs in that K is 0.6, 0.8, and 1.0, but in case that K is 1.5, subsidence of about 0.67m occurs as in Fig. 11 and the rock mass around the surface rises by being pushed next above the gangway as in Fig. 10(a). This is analyzed both by being lowered the input data of joint and by the high horizontal stress. It is decided that K is 1.0 for analyzing the volumetric expansion ratio according to the behavior of block, because the amount of the surface subsidence according to the variation of K as in Fig. 11 decreases constantly regarding K in case that K is below 1.0.



(a) K-ratio=1.5 (b) K-ratio=1.0

(c) K-ratio=0.8 (d) K-ratio=0.6

Fig. 10. Results of K-ratio analysis

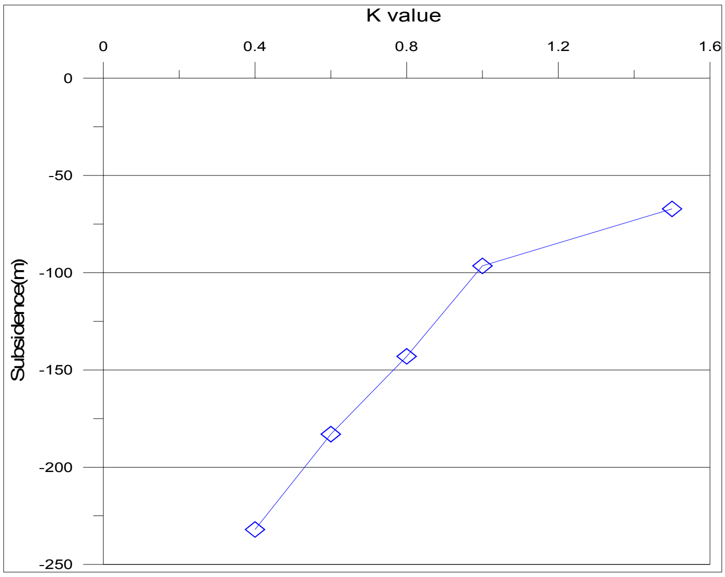


Fig. 11. Subsidence developed with the change of each K-ratio

3.2 The volumetric expansion ratio according to behavior of block

In the discontinuum analysis, the property of the surface of discontinuity, in particular, is cohesion and friction angle used as input data in stiffness and fracture criterion of the surface of discontinuity. In this analysis, the property of rock mass uses the same value used in the analysis by K, and in order to induce successive collapse of block it is made to have difference between the value of normal stiffness and shear stiffness in a vertical and horizontal joint generated in region 1 as in Table 3, and by increasing cohesion in relation with fracture criterion the behavior of collapse is analyzed. As analysis model has the depth of 20m, and width of 10m as in Fig. 12, in order to analyze the effect of the volumetric expansion ratio by a collapse of block, the heigh of gangway is set to 8m in order that the maximum volumetric expansion ratio of reaches 40%. Moreover, to analyze the effect of block size it is analyzed in case that the block size is 1m and 2m.

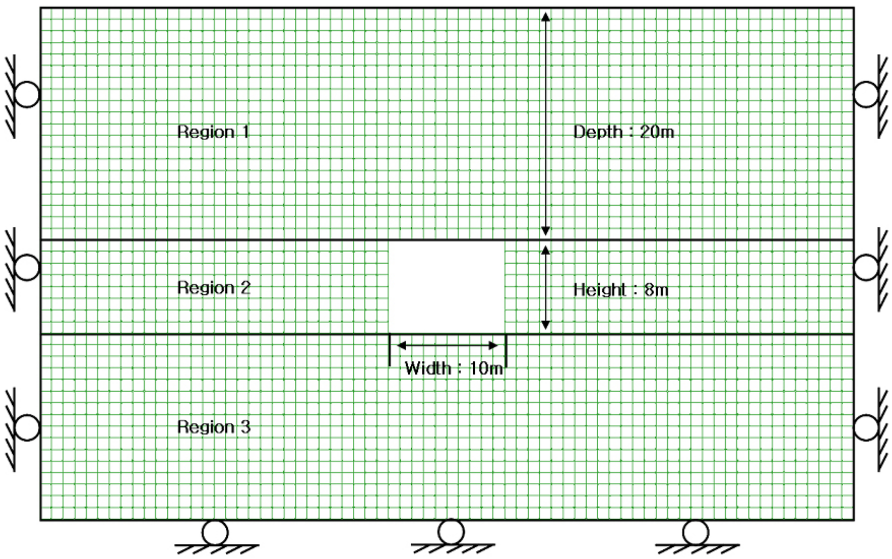


Fig. 12. Model for the volumetric expansion ratio analysis(70×44m)

Table 3. Input data of joint property

		Normal stiffness (MPa/m)	Shear stiffness (MPa/m)	Cohesion (MPa)	Friction angle(°)
Region 1	Horizontal joint	15	35	0.030	10.8
	Vertical joint	5	25	0.030	10.8
Region 2		40	40	0.040	11.4
Region 3		45	45	0.060	12.0

Table 4 shows the results of subsidence according to the variation of cohesion. Both in block size of 1m and 2m, subsidence tends to decrease as cohesion increases. But block size of 2m is not collapsed in the cohesion of 0.11MPa. This is caused by the block size and because contact area between blocks is larger than that of the block size of 1m, it is analyzed that the behavior of block is not active than that of the block size of 1m within the width of gangway. Also, in case of the block size of 1m, the surface subsidence occurs until the cohesion of 0.11MPa, but in case of the cohesion of 0.13MPa it does not occur because the collapse of block stopped and stress arch is generated so that ground becomes stable. If, in this case, vertical stress increases by structures on the ground and other influential factors, subsidence can occur.

If the subsidence area is the same, from the result of Table 4 the volume of subsidence is calculated as in Table 5.

The volumetric expansion ratio according to the variation of cohesion from the volume of subsidence, gangway, and an overburden to be collapsed(Table 6, Fig. 13). The subsidence occurs greatly because the lower cohesion is, the more active separation between blocks is. Therefore, in the value of property of fixed parameters(jkn, jks, jfric) subsidence does not occur because separation between blocks is not active in case of more than the cohesion of 0.11MPa. Also, the collapse in the block size of 1m stopped in case of the cohesion of 0.13MPa, but the volumetric expansion ratio calculated from both the volume of an overburden to be collapsed and stacking dome shows 49.36%.

This numerical analysis, to analyze the variation of the volumetric expansion ratio according to behavior of block unifying the shape and size of the block, is analyzed according to the variation of cohesion. As a result, it is analyzed that the variation of the volumetric expansion ratio occurs by the cohesion, that is, fracture criterion parameter of the surface of discontinuity. It is possible to predict not only the subsidence influence zone and the subsidence amounts but also the subsidence prediction, in case that subsidence analysis considering the volumetric expansion ratio is analyzed using UDEC, if parameters that influence the behavior of block is considered, a distribution pattern of joint set is departmentalized suited for in-situ condition, and then, the separation behavior of block is analyzed.

Table 4. The subsidence developed with the change of each joint cohesion

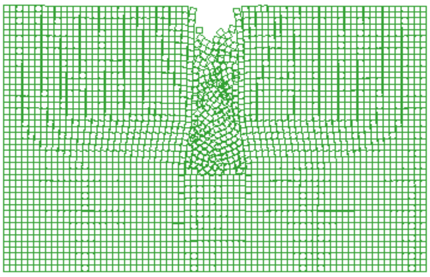
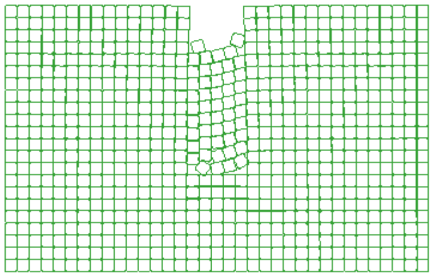
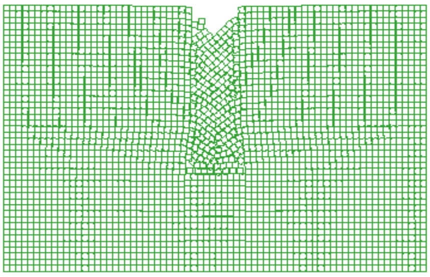
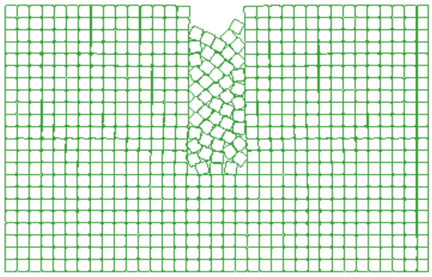
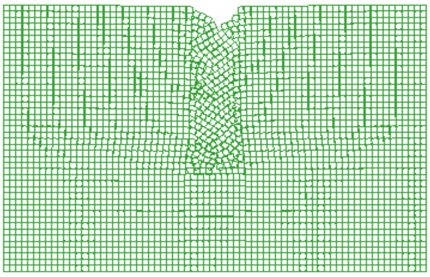
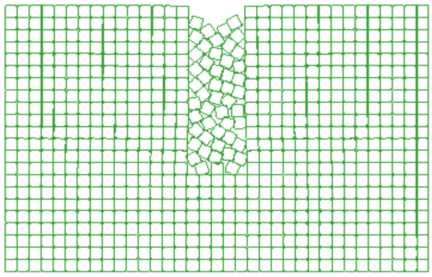
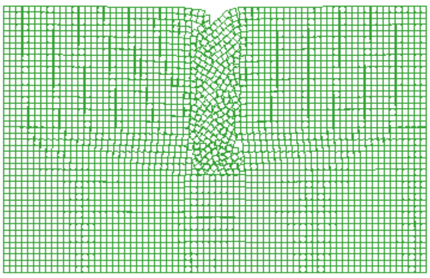
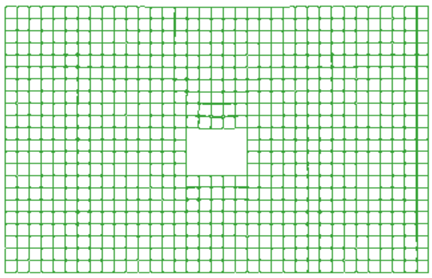
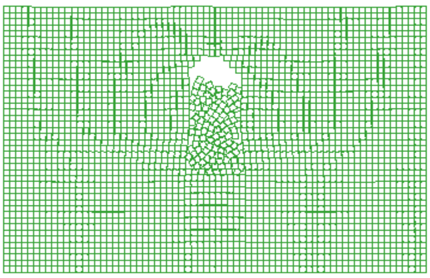
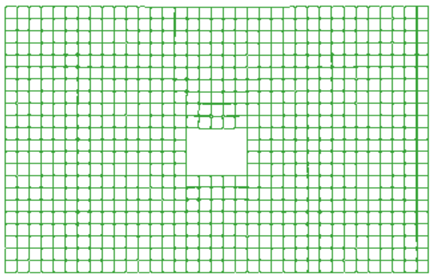
Cohesion(MPa)	Block size - 1.00m	Block size - 2.00m
0.03		
	321580 step	411690 step
0.07		
	431580 step	411690 step
0.09		
	585580 step	411690 step
0.11		
	531580 step	411690 step
0.13		
	431580 step	411690 step

Table 5. The subsidence volume developed with the change of each joint cohesion

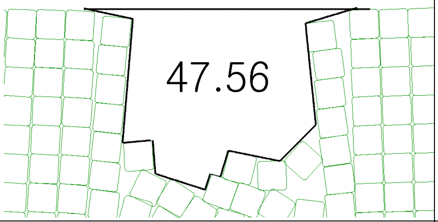
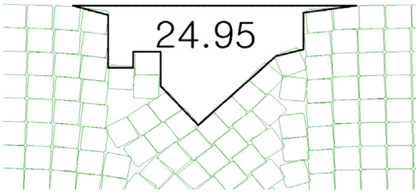
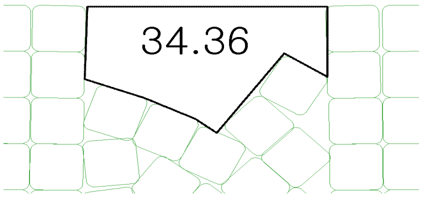
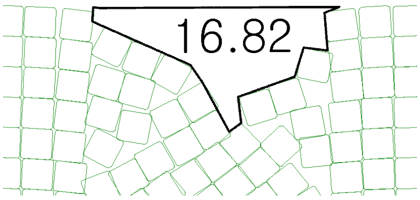
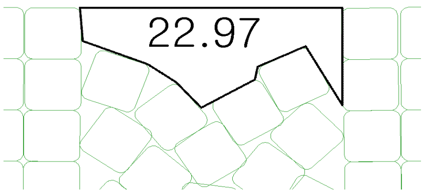
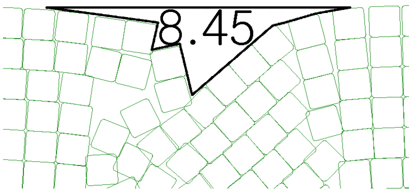
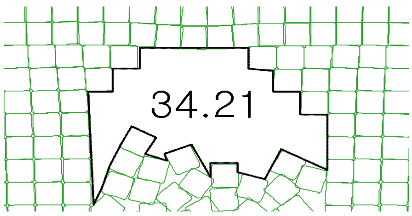
Cohesion(MPa)	Block size - 1.00m	Block size - 2.00m
0.03	 321580 step	 411690 step
0.07	 431580 step	 411690 step
0.09	 585580 step	 411690 step
0.11	 531580 step	- 411690 step
0.13	 431580 step	- 411690 step

Table 6. Volumetric expansion ratio developed with the change of each joint cohesion

Cohesion (MPa)	Block size (m)	V_i(㎥)	V_o(㎥)	V_{ss}(㎥)	V_f(㎥)	B(%)
0.03	1.00	200.00	80.00	47.56	232.44	16.22
	2.00			51.25	228.75	14.38
0.07	1.00	200.00	80.00	24.95	255.05	27.53
	2.00			34.36	245.64	22.82
0.09	1.00	200.00	80.00	16.82	263.18	31.59
	2.00			22.97	257.03	28.52
0.11	1.00	200.00	80.00	8.45	271.55	35.78
	2.00			–	–	–
0.13	1.00	111.00	80.00	34.21	165.79	49.36
	2.00			–	–	–

* V_i : the final volume before a collapse
V_o : the volume of an opening
V_{ss} : the volume of a subsidence
V_f : the final volume after a collapse
B : the volumetric expansion ratio

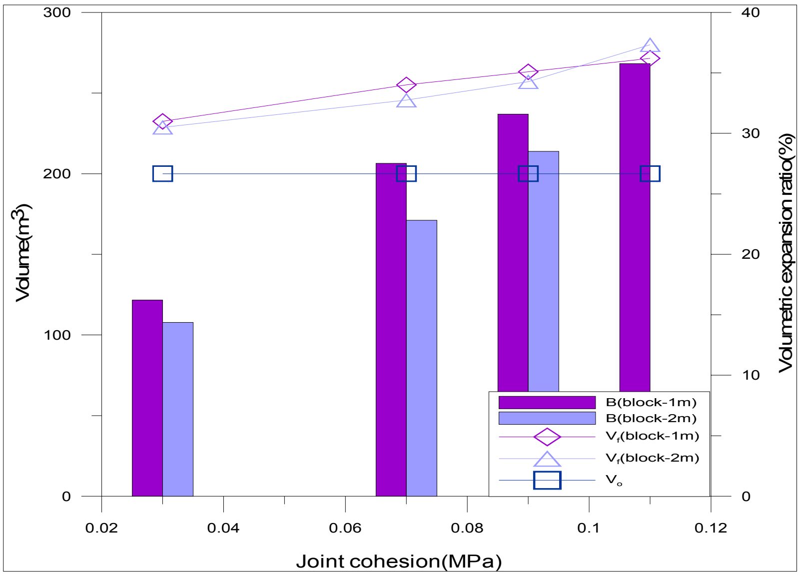


Fig. 13. Relationship between volume and volumetric expansion ratio according to cohesion(B: volumetric expansion ratio, V_i: initial volume of before a collapse, V_f: final volume of after a collapse. V_o: volume of an opening)

3. Conclusion

In this study, numerical analysis using theoretical consideration and discrete element method about the volumetric expansion ratio of rock mass, the cause that the depth of the surface subsidence is lower than the height of an opening, is conducted.

Theoretically, in order to analyze the subsidence influence zone and the subsidence amounts according to the subsidence pattern, using the model of three dimensions considering the radius of subsidence influence and the depth, equation about the volumetric expansion ratio and subsidence is induced. As a result, the maximum volumetric expansion ratio can vary according to the radius of subsidence influence and the depth about the gangway having a certain volume and it can be influenced not by the depth of gangway, but largely by the radius of subsidence influence.

Numerical analysis in this study considers K influencing the behavior of block, applying low value of property about generating both vertical and horizontal joint. Also, it is conducted considering the volumetric expansion ratio giving numerical analysis the variation of cohesion which is fracture criterion of the surface of discontinuity. Consequently, the behavior of block caused by low value of property of joint is influenced by K, and by the variation of cohesion the variation of the volumetric expansion ratio according to the behavior of block can be analyzed. Thus, in case of analyzing discontinuum, if the study about the volumetric expansion ratio considering departmental joint formations suited for in-situ condition, the cohesion and friction angle which are a fracture criterion of the surface of discontinuity is conducted persistently, it is possible to calculate subsidence close to in-situ.

In this study, even though the variation pattern of the volumetric expansion ratio according to theoretical consideration about the volumetric expansion ratio is conducted and the behavior of block is analyzed in a way of numerical analysis, because this is a qualitative result according to trend analysis, it is more likely to utilize in the field of subsidence prediction if the volumetric expansion ratio is reflected in numerical analysis through more correct in-situ investigations and analysis about dangerous subsidence area.

Reference

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