Deformation Behaviour of Metamorphic Tuff from Plate Loading Test

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요 지

본 논문에서는 건설 중인 국내의 한 지하 원유비축기지의 기반암인 변성응회암의 변형특성을 파악하고 변형계수를 결정하기 위하여 평판재하시험 및 불연속체 수치해석을 수행하였다. 평판재하시험에서는 직경 1m의 flat jack을 이용하여 최대 14MPa의 하중을 기반암에 가하고 이에 대한 반력장치로서 록 앵커 시스템을 이용하였다. 본 시험으로부터 얻어진 변형계수 결과치는 실내시험, 이축압축시험, 공내재하시험 등에서 구한 값들과 비교되었다. 그 결과, 평판재하시험에서 구한 변형계수는 신선한 암편 탄성계수의 약 50% 정도인 것으로 나타났으며, 현지 기반암의 변형계수는 암반에 분포하는 절리들로 인하여 25-35GPa의 범위에 속하는 것으로 판정되었다. 또한 시험 부지내에 분포하는 여러 불연속면들을 고려한 불연속체 해석을 실시하여 평판재하시험을 모사하고 절리들이 암반의 변형특성에 미치는 영향을 분석하였다.

Abstract

This paper presents the results of plate loading test and discontinuum analysis, carried out to study the deformation behaviour and determine the deformation modulus of metamorphic andesitic tuff found at the site of a underground oil storage facility in Korea. In the plate loading test, the maximum pressure of 14MPa was applied to the bedrock by using a flat jack(1m in diameter) and the rock anchor system for the reaction against the applied pressure. The values of deformation modulus obtained from this test were compared with those of laboratory test, biaxial test and pressuremeter test. The deformation modulus from plate loading test was generally about half of the intact rock modulus, and the mass modulus of the bedrock at the test site may be affected by discontinuities and ranges between 25 and 35GPa. Discontinuum analysis was also performed to simulate plate loading test and study the influence of discontinuities on the deformability of rock mass by simulating the presence of joints at the test area.

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1. Introduction

A correct estimation of the deformability of rock mass is essential to the design of various underground excavations. The plate loading test, an effective method determining the deformability of rock mass, is generally performed in a test adit or small tunnel in order to utilize restraint columns to secure the reaction against the applied loading. However, the plate loading test described in this paper was carried out in a large tunnel by using the rock anchor system for the reaction against the applied pressure.

The modulus obtained from this test was compared with those from laboratory test, biaxial test and pressuremeter test. Numerical simulation for this test using Universal Distinct Element Code(UDEC), which can model the presence of joints at the test area, was performed to study the influence of discontinuities on the deformability of rock mass.

2. Site Description

The underground facility for oil storage at the test site is mainly composed of six storage caverns, construction tunnels, two shafts and water curtain tunnels, as shown in Figure 1.(Lee et al., 1995). Six storage caverns, to be left unlined at EL.(−)30~EL.(−) 60m, are aligned parallel to each other in the direction of N80°W. Each of these caverns has horseshoe shape with its dimension is 18m wide, 30m high and 400~600m long. The construction tunnel has also horseshoe shape with the dimension of 8m wide and 7.5m high.

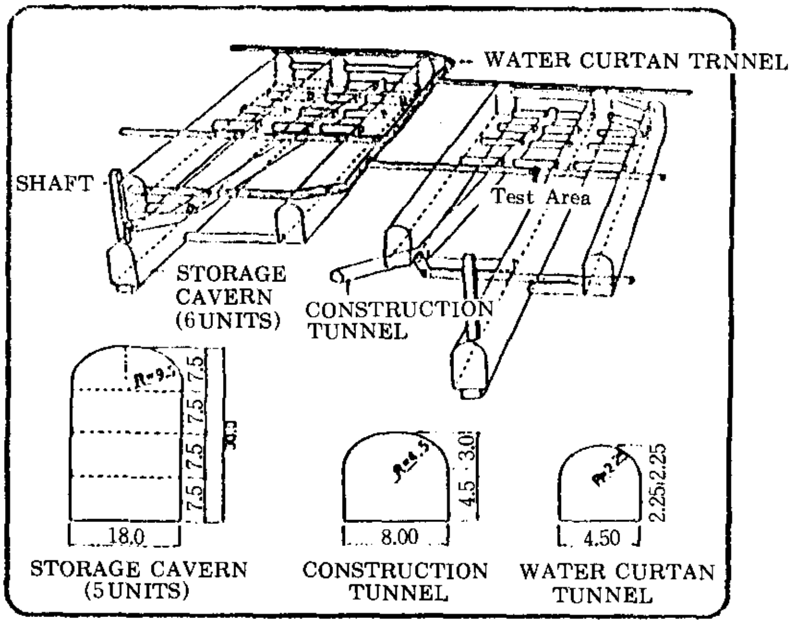

Figure 1. General layout plan for oil storage facility and test area

The tunnel elevation changes from EL.(+)10.0m at the entry to EL. (−)60.0m at the bottom level of cavern with about 12% slope in between these two levels.

The bedrock at the site area is metamorphic andesitic tuff of the Late Cretaceous Period. The tuff is dark grey, very tight and has welding texture at the boundary of rock fragments as a thermo-metamorphic evidence. There are three joint sets (N70~80°E/70~80°NW, N10°E/70~80°SE and N45°W/20°SW) and random joints in the bedrock. These joints are in general tightly-healed, but locally coated or filled with calcite. The mechanical properties of the intact rock obtained from site investigation is shown in Table 1. The average uniaxial compressive strength is about 250MPa and the average modulus of elasticity is 8.3×10^4MPa, which indicates that the metamorphic tuff at the site could be classified as rock having very high strength and medium modulus ratio(Deere.and Miller 1966).

Table 1. The mechanical properties of intact rock

Property	No. of Sample tested	Average value	Range
Uniaxial compressive strength(MPa)	12	250	215~331
Tensile strength(MPa)	12	22	16~31
Elastic modulus($\times10^4$MPa)	12	8.3	7.03~9.66
Poisson's ratio	12	0.23	0.21~0.25
Internal friction angle(°)	4	51.5	49~54
Cohesion(MPa)	4	53	48~59

3. Plate Loading Test

3.1 Test condition at the site

Plate loading test was carried out at the bottom of one of construction tunnels, as shown in Figure 1. The overburden at this location was about 250m. The bedrock condition at the test site was evaluated by logging core samples from the instrumentation hole in the center of test area, drilled to a depth of 6.7m. From the careful inspection of core samples, it was found that a total of 10 joints were encountered at the test site, as shown in Figure 2. Most of these joints were mainly tightly-healed, but two joints were coated or filled with calcite.

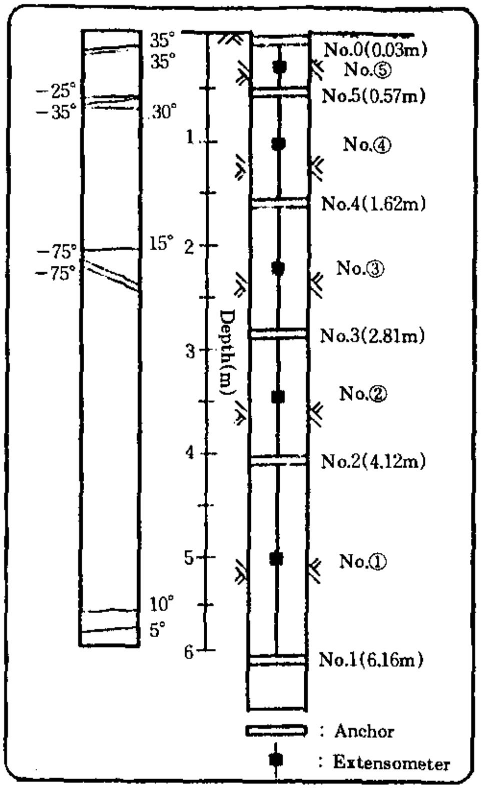

Figure 2. Rock condition at test site and arrangement of extensometers and anchors.

3.2 Test procedure

The test system consisted of three main parts : loading apparatus, rock anchor system for the reaction and instrumentation system, as shown in Figure 3. The maximum pressure of 14MPa was applied to the test area by using a flat jack with diameter of 1m and the maximum stroke of 35mm. The flat jack was loaded by flat jack drive to convert small pneumatic pressure to the intensified hydraulic pressure. The reaction anchor system is composed of 12 Dywidag bars, having the total length of 17.2m, bonded length of 6.1m and diameter of 58mm, and reinforced concrete block to fasten anchors. The instrumentation hole (diameter of 76mm) was core-drilled to a depth of 6.7m and six anchors for the extensometer installation were fixed at the depths of 0.05m, 0.57m, 1.62m, 2.81m, 4.12m and 6.16m below the surface, as shown in Figure 2. Each of five extensometers (vibrating-wire type) was installed in-between two adjacent anchors to measure the relative displacement between two anchor points.

The test load was applied in a cyclic manner with pressures of 4, 8, 12, and 14MPa and corresponding rock displacements were monitored and recorded continuously by using data

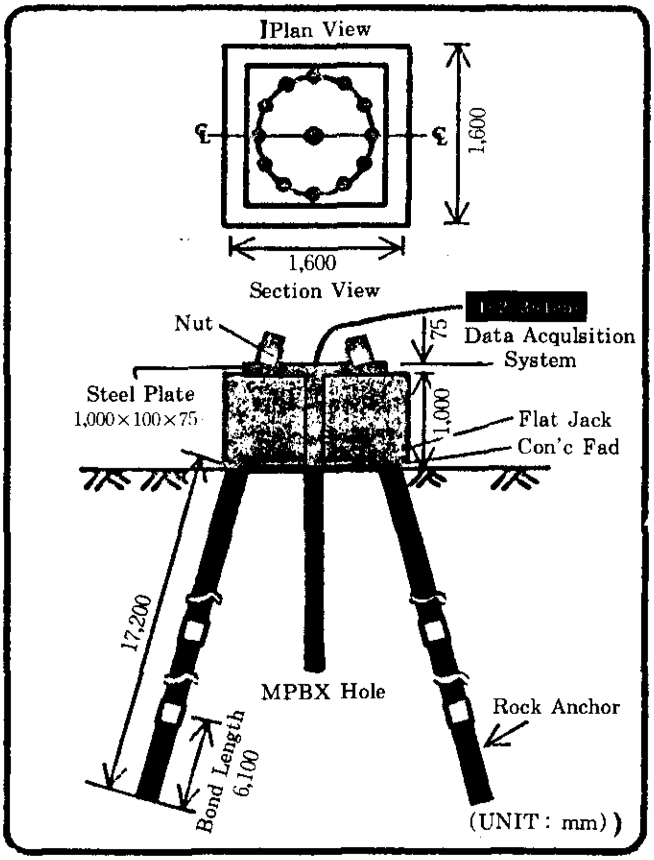

Figure 3. Layout plan for plate loading test arrangement

acquisition system. The test pressure was applied in a rate of 0.1MPa/min. and kept for about an hour at the peak pressure of each cycle.

3.3 Test Results

Displacements measured by 5 extensometers are plotted against the time for the four cycles of test in Figure 4. Displacement plotted in this Figure is relative in nature, since the measured displacement by extensometer is rock deformation of the test section separated by two adjacent anchors.

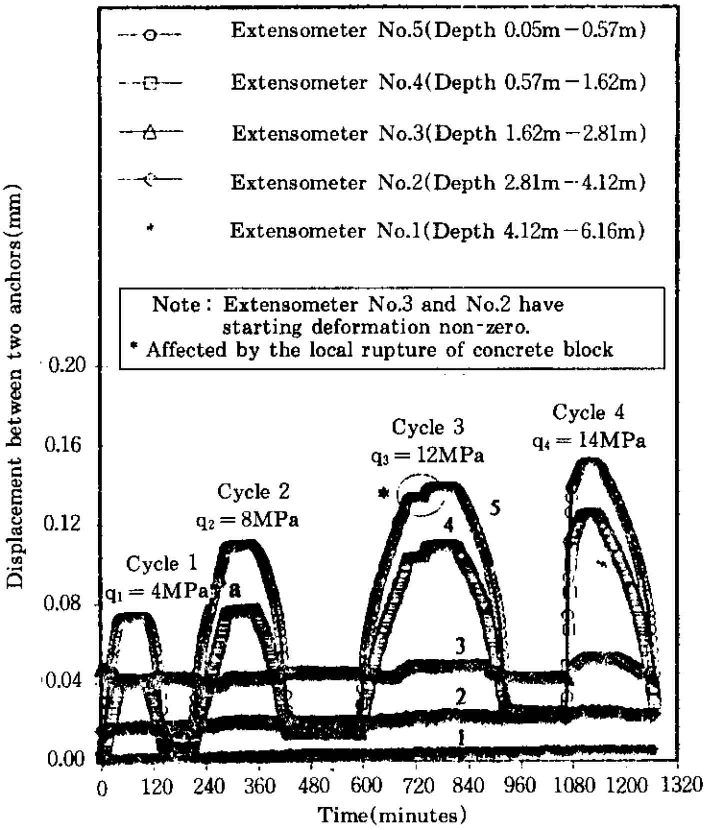

Figure 4. Plot of relative displacements, time and applied stresses during four different cycles

As can be seen in this Figure, extensometers near the surface, ie. No. 4 and 5, show much distinctive and pronounce deformation response against the applied stress compared to those at deeper depths. This may be attributed partially to higher stress distribution near the surface and partially to the fact that the bedrock at the surface has several joints near the surface. It is also interesting to note that extensometers at deeper depths, ie. No. 1 and 2, show very consistent increase in displacement with stress increase, though the magnitude is so small that it may be neglected in the practical point of view. Displacement measured at Extensometer No. 3 level shows the initial dilatancy behaviour, contrary to all the other measurements. This unusual behavior may be attributed to the presence of calcite seam at this test level (depth of 2.3m), as shown in Figure 2. This phenomenon may be clearly demonstrated in Figure 5. In this Figure, peak strains of each cycle have been calculated by using peak displacement and the thickness of the test section between two anchor points and plotted against the applied stress at each cycle for extensometers No. 3, 4 and 5.

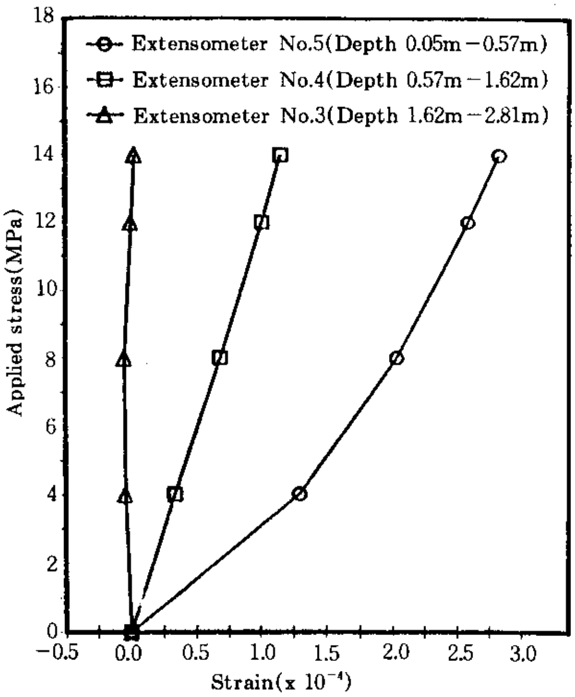

Figure 5. Applied stress vs. strain of test section between two anchor points

It may be noted from the results of Extensometer No. 3 that the bedrock at this level shows the dilatant behavior due to the presence of calcite seam. It can also be observed from this Figure that Extensometer No. 5 shows much higher strains compared with Extensometer No. 4, which indicates that the bedrock near the surface takes substantial portion of the applied load since the number of joints included in both test sections is comparable to each other as can be seen in Figure 2.

Cumulative (or absolute) displacements at several depths have been calculated by assuming zero displacement at the anchor No. 1(6.16m below ground surface) and adding displacements of test section(s) successively from the bottom to the surface. The cumulative displacements under the applied stress of 14MPa are plotted against the depth below ground surface in Figure 6. From this Figure, it may be observed that the surface displacement is about 0.3mm under the applied stress of 14MPa, which suggests that the bedrock at the site be very competent. The displacement at the depth of 1.5m is about 10% of the surface displacement, which indicates that most displacements occur near the loading surface.

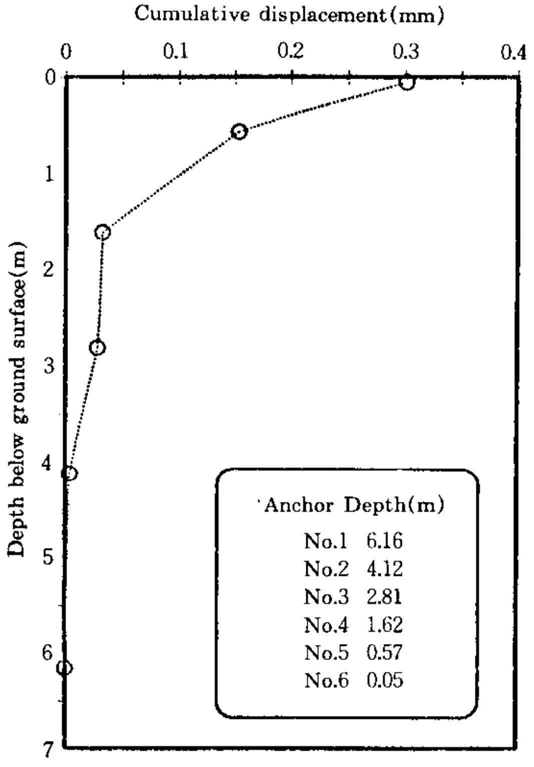

Figure 6. Measured cumulative displacements using extensometers at different depths

For the uniform load distributed over the circular area with a hole in the center, the deformation modulus(E) can be expressed as the following equation :

$$E = \frac{2Q(1-\nu^2)}{W_Z}\left(\sqrt{R_2^2+Z^2}-\sqrt{R_1^2+Z^2}\right) + \frac{Z^2Q(1+\nu)}{W_Z}\left(\frac{1}{\sqrt{R_1^2+Z^2}} - \frac{1}{\sqrt{R_2^2+Z^2}}\right)$$

where Q is the applied pressure(MPa), ν is poisson's ratio, W_z is displacement at depth Z(m), R_1 is inner radius of flat jack(m), R_2 is outer radius of flat jack(m) and Z is the distance(m) from the loaded surface to the point where displacement is calculated (Coulson et al., 1978). Calculated deformation moduli from this test are plotted against the depth in Figure 7. It is observed from this Figure that deformation moduli range from 37GPa to 43GPa, with an average value of 40GPa.

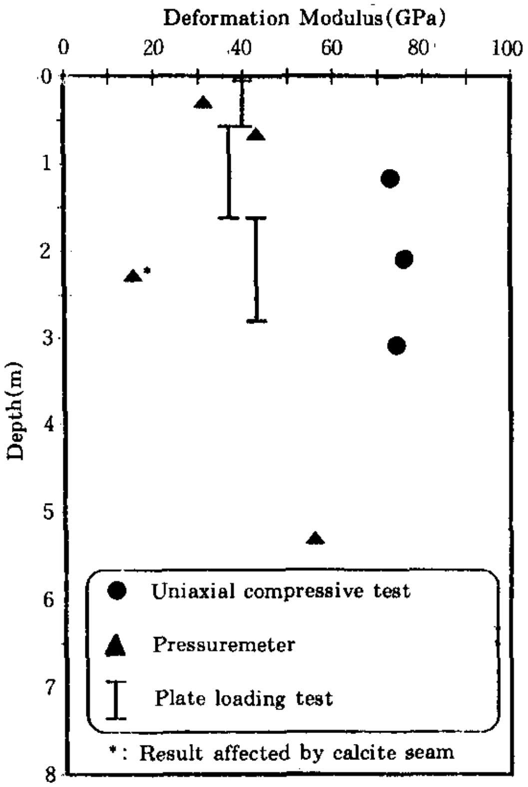

Figure 7. Variation of modulus with depth from different type of tests

For the purpose of comparison, moduli values were determined from laboratory test on the intact rock specimen from the center instrumentation hole and pressuremeter test carried out in the same hole. These results are plotted together with the results of plate loading test against the depth, as shown in Figure 7. As can be seen from this Figure, the deformation modulus values obtained from plate loading test are almost constant over the depth, about 50% of those obtained from laboratory test, which reflects the influence of joints below the plate on the deformation behaviour of the rock.

In order to study the effect of joints, the deformation modulus values obtained from different type of tests are plotted against the loaded area in Figure 8. All the results presented in this Figure were obtained from the tests performed for the instrumentation hole, except biaxial test which was carried out as a part of stress measurement at another location. It may be observed from this Figure that deformation modulus of the bedrock decreases with the increase in test area, which reflects the effect of joints and suggests that the mass modulus of the site approach to the value of about 25 to 35GPa.

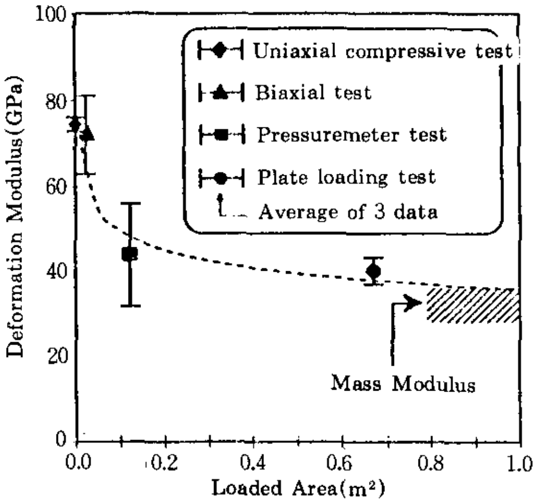

Figure 8. Variation of modulus with loaded area from different type of tests

4. Numerical Analysis

Discontinuum analysis using UDEC was carried out to study stress change and displacement due to the applied stress by modelling the rock mass as a mixture of intact rock and set of joints.

4.1 Model description

The model used in the 2-dimensional numerical analysis is shown in Figure 9. As can be seen from this Figure, a total of 10 intersecting joints were modelled, by using the results of core logging for the instrumentation hole and surface geological mapping of the test area. The joint contact was assumed to behave as a Coulomb slip joint with constant elastic normal and shear stiffnesses. The block used in the analysis has the size of 10m in depth and 10 m in width. One meter wide line load of 14MPa was applied on the ground surface of this block.

The joint properties used in this analysis are summarized in Table 2. For all the joints, values of JRC, JCS, dilation angle and peak friction angle were estimated by using the method suggested by Barton(1976). The values of joint stiffnesses (K_n, K_s) for tightly-healed joints were obtained from joint compression and shear tests in the laboratory.

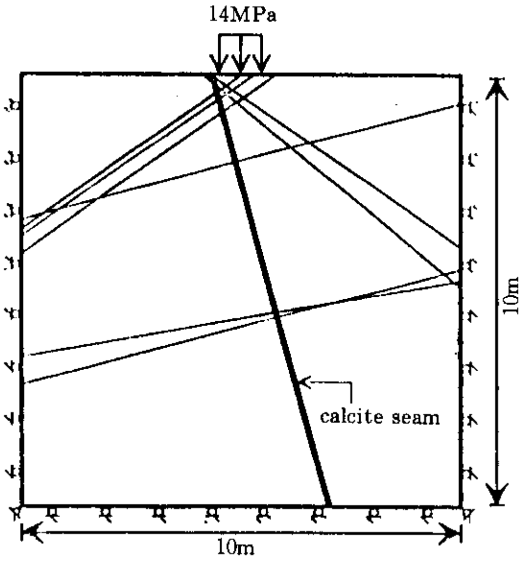

Figure 9. Rock mass block showing discontinuities and boundary conditions for UDEC analysis

Table 2. The joint properties used in UDEC analysis

Properties	Tightly-healed joints
JRC	8 ~ 12
JCS(MPa)	60
Dilation angle (°)	13
Peak friction angle (°)	43
Normal stiffness(K_n, MPa/m)	53,700
Shear stiffness(K_s, MPa/m)	1,530

4.2 Analysis results

Displacements obtained from this analysis are plotted against the depth in Figure 10, together with the results of plate loading test presented in Figure 6. As can be seen from this Figure, displacements obtained from the analysis are in general comparable to the test results in the magnitude and variation of vertical displacement with depth, which indicates that discontinuum analysis performed is capable of simulating the deformation behaviour of jointed rock mass under the compressive loading.

Displacement contours within rock mass due to the applied stress are shown in Figure 11. It is clear from this Figure that the vertical displacement pattern is affected by the presence of joints. Due to the spatial distribution of joints under the loading surface, most of large displacements occurred along and on the right-hand side of subvertical joint(calcite

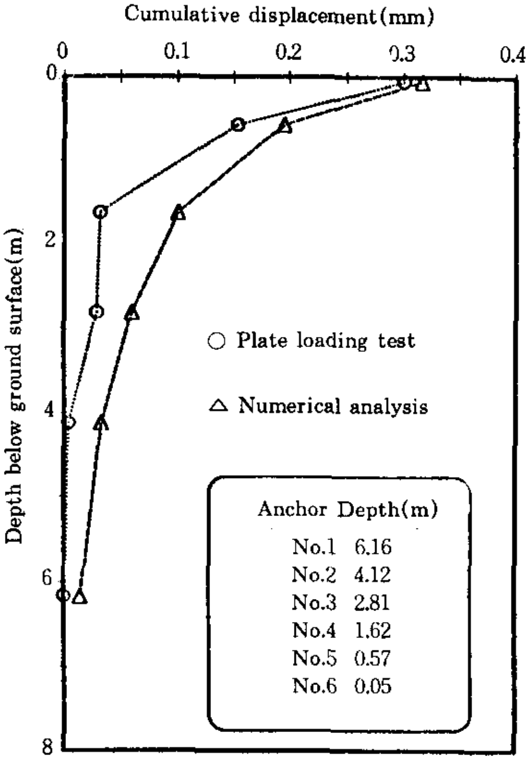

Figure 10. Vertical displacements at different depths obtained from plate loading test and UDEC analysis

seam), and at the depth of about 1m which is one diameter. It is also interesting to note that jointed blocks under the loading surface seem to move toward the right-hand side along three joints dipping 30° and 75° respectively, which indicates that the spatial distribution of joints may govern the displacement behaviour under the applied stress.

In Figure 12, the distribution of vertical stress due to the surface loading of 14MPa is shown together with 20% of applied pressure bulb for the isotropic case. From this Figure, it may be observed that the stress distribution obtained is substantially affected by the presence of joints, as in the case of displacement. The shape of stress increment distribution seems to be significantly altered from the isotropic case due to the joint dipping 75° toward the right-hand side. The 20% pressure contour from the analysis extends to about 5m below the loading surface, following the direction of this joint, while that of the isotropic case reaches only to the depth of 1m.

From the observation of results shown in Figures 10, 11 and 12, it may be concluded that discontinuum approach is useful for the simulation of complex behaviour of jointed rock

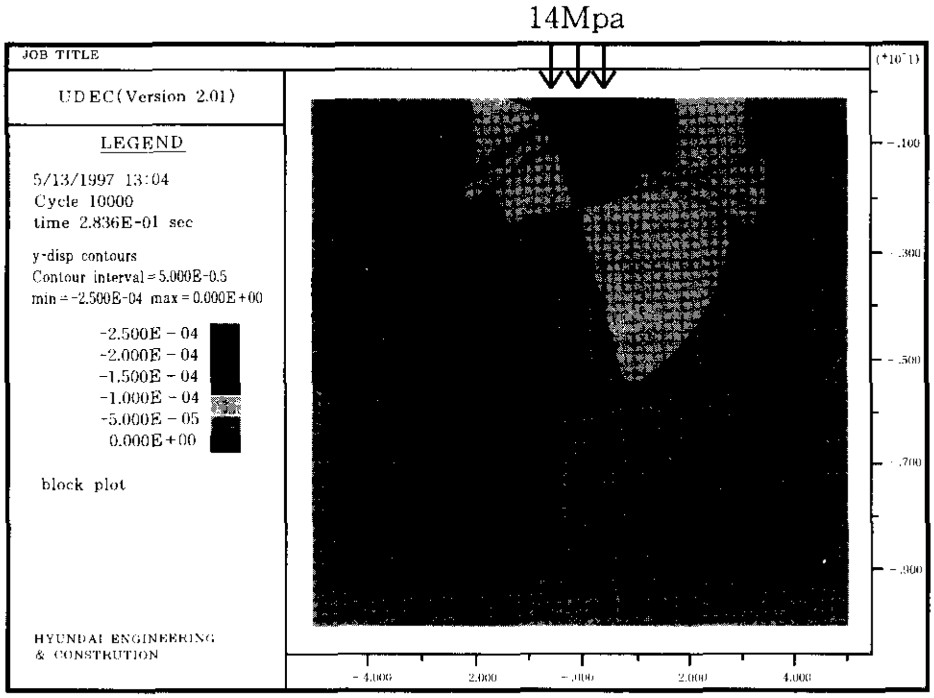

Figure 11. Vertical displacement distribution UDEC analysis

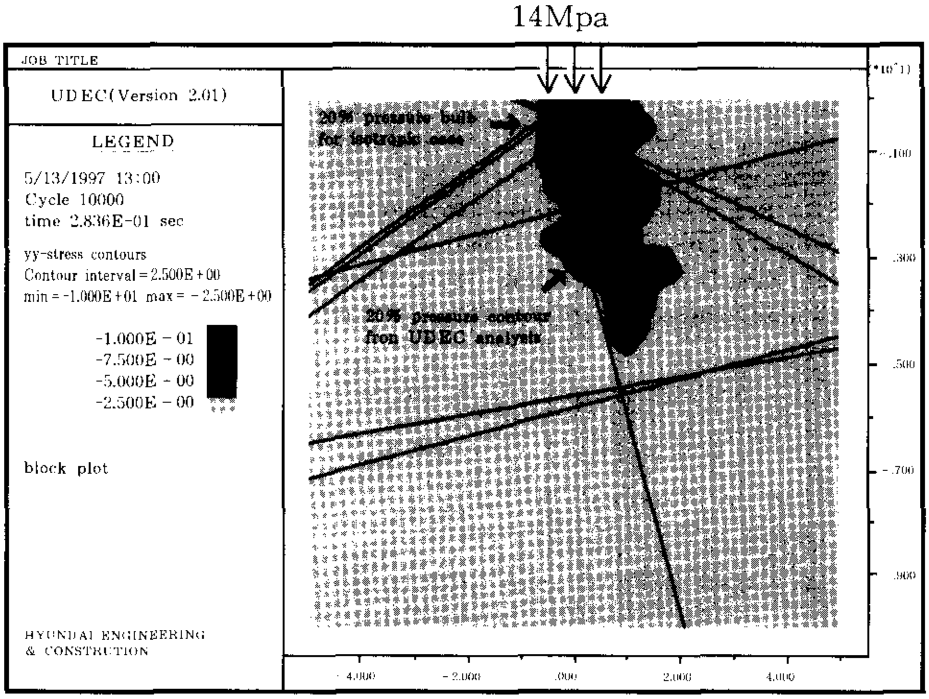

Figure 12. Vertical stress distribution from UDEC analysis

mass under compressive loading, when appropriate joint model and input parameters are adopted in the analysis.

5. Conclusions

Plate loading test with the applied pressure of 14MPa was carried out to study the deformation behaviour of metamorphic andesitic tuff. Discontinuum analysis was also performed to study the influence of discontinuities on the deformability of rock mass. Based on the results of these studies, the following conclusions may be drawn :

1. Bedrock at the site is competent and the deformation modulus is constant over the depth, about 50% of the intact modulus of rock due to the presence of several joints.
2. The deformation modulus of rock mass, estimated from several different tests having different loading areas, approaches to about 25 to 35 GPa at this site.
3. Discontinuum analysis with realistic joint model turned out to be useful for the better simulation of complex behaviour of jointed rock mass under compressive loading.

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