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Formulation and Implementation of Effective Stress Coefficient of Rock to FEM

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The authors tried to evaluate four types of effective stress coefficients of rock; one under hydrostatic pressure (Biot's effective stress coefficient), one for peak strength, one for residual strength and one for fractured rock. The types of rock considered were Kimachi sandstone, Bibai sandstone, Inada granite and Shikotsu welded tuff. Biot's effective stress coefficient obtained by conventional hydrostatic compression test method and the coefficient for peak and residual strengths obtained by the modified failure envelope method which was newly developed by the authors decreased with confining pressure. The effective stress coefficient for fractured rock was evaluated under hydrostatic pressure for post-failure specimens and it was slightly smaller than one. An equation which represents the coefficient by stress was derived and implemented into a FEM software. This paper explains the equation and the example of calculation results.
1. Introduction

The authors have tried to evaluate four types of effective stress coefficients of rock: one under hydrostatic pressure (Biot’s effective stress coefficient), one for peak strength, one for residual strength and one for fractured rock. The types of rock considered were Kimachi sandstone, Bibai sandstone, Inada granite and Shikotsu welded tuff. Biot’s effective stress coefficient obtained by conventional hydrostatic compression test method and the coefficient for peak and residual strengths obtained by the modified failure envelope method which was newly developed by the authors decreased with confining pressure. The effective stress coefficient for fractured rock was evaluated under hydrostatic pressure for post-failure specimens and it was slightly smaller than one. An equation which represents the coefficient by stress was derived and implemented into a finite element (FE) software. This paper describes the equation and the example of FE calculation results.

2. Stress dependency of effective stress coefficient

Taking an effective normal stress $\sigma_n'$ on the rupture plane which is assumed to be inclined at $30^\circ$ from the maximum compressive stress, the four effective stress coefficients $\alpha$ for Kimachi sandstone can be roughly approximated by a line

$$\alpha = A - B\sigma_n'$$

except for that of fractured rock (Fig.1) where $A$ and $B$ are constants. Then the coefficients can be estimated from the normal stress $\sigma_n$ on the assumed rupture plane and pore pressure $P_p$ as

$$\alpha = \frac{A - B\sigma_n' - BP_p}{1 - BP_p}.$$  \hspace{1cm} (2)

Fig. 1  The four effective stress coefficients for Kimachi sandstone as a function of effective normal stress (Dassanayake et al. 2015)

3. Distribution of stresses and stress severity around an underground cavern

A 2-D elastic FE calculation was carried out to examine the effect of stress dependent effective stress coefficient. A 60 m wide and 50 m high quarter rock mass consisting of Kimachi sandstone and, a 40 m wide and 32 m high cavern in the rock mass were assumed. Horizontal displacement was confined at the left and right boundaries. Vertical displacement was confined at the bottom. A vertical pressure of 15 MPa was applied on the top. A pore pressure of 5 MPa was applied from the top and the right boundaries. The bottom and the left boundaries were assumed to be impermeable. The cavern was assumed to be backfilled by bentonite. The mechanical properties were assumed as Table 1. The strength of backfill was assumed to be very large so that its stress severity could be ignored.

Modified stress severity $S_b$ was calculated as

$$S_b = \frac{\sigma}{\sigma_C}$$  \hspace{1cm} (3)

for compressive failure (Fig. 2). If more than one principal stresses were tensile,

$$S_b = -\frac{\sigma}{\sigma_T}$$  \hspace{1cm} (4)
was also calculated. The negative sign denotes tensile failure. The absolute values of the two severities were compared and the bigger one was used.

The effective stress coefficient (Fig. 3) was assumed to be zero (a), unity (b), as Kimachi sandstone \((A = 0.976\) and \(B = 0.0096\) (MPa\(^{-1}\)), (c)), as Kimachi sandstone but 10 times \(B\) (d) or 0.5 (e). Of course distributions of the maximum (Fig.4) and minimum (Fig. 5) stresses as well as that of stress severity (Fig. 6) were extremes for (a) and (b), and those for (e) were in between. The distributions for (c) and (d) were the same and rather similar to (b). This would be because the stress of most areas was low and the coefficient was large even if the stress was high and the coefficient was low in limited areas for (c) and (d).

4. Conclusion
The stress dependency of effective stress coefficient was formulated and installed in FE stress analysis. The results for stress dependent effective stress coefficient were slightly but different from those assuming that the coefficient was unity. It can be concluded that pore pressure should not be ignored of course. The most accurate solution would be obtained with stress dependent effective stress coefficient. However, if estimation of the stress dependent coefficient is difficult, it would rather be better to assume the coefficient to be unity than to use a constant coefficient obtained under a high confining pressure because it may induce underestimation of stress severity.

Acknowledgement
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Table 1  Mechanical properties of rock mass and backfill (a: Amo et al. (2016), b: Jung et al. (2001), c: Alam et al, d: Kwon & Cho (2008))

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<tr>
<th></th>
<th>Tangent modulus (GPa)</th>
<th>Poisson's ratio</th>
<th>Indirect tensile strength (MPa)</th>
<th>Saturated UCS (MPa)</th>
<th>Internal friction angle (°)</th>
<th>Porosity (%)</th>
<th>Permeability (m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kimachi sandstone</td>
<td>21.5(^a)</td>
<td>0.25(^a)</td>
<td>3(^b)</td>
<td>20.5(^c)</td>
<td>22(^c)</td>
<td>18.5(^c)</td>
<td>3 \times 10^{-18}(^c)</td>
</tr>
<tr>
<td>Backfill(^d)</td>
<td>0.0694</td>
<td>0.22</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.80</td>
<td>1 \times 10^{-18}</td>
</tr>
</tbody>
</table>

Fig.2  Failure criterion and modified stress severity calculation.
(a) Pore pressure was ignored

(b) $\alpha = 1$

(c) Stress dependent $\alpha$

(c) Strong stress dependent

(b) $\alpha = 0.5$

Fig. 3  Distribution of effective stress coefficient.
(a) Pore pressure was ignored

(b) $\alpha = 1$

(c) Stress dependent $\alpha$

(c) Strong stress dependent

(b) $\alpha = 0.5$

Fig. 4 Distribution of maximum compressive stress.

References
(a) Pore pressure was ignored

(b) $\alpha = 1$

(c) Stress dependent $\alpha$

(c) Strong stress dependent

(b) $\alpha = 0.5$

Fig. 5 Distribution of minimum compressive stress.

(a) Pore pressure was ignored.  
(b) $\alpha = 1$.  
(c) Stress dependent $\alpha$  
(c) Strong stress dependent  
(b) $\alpha = 0.5$.  

Fig. 6 Distribution of stress severity.