Stability Analysis and Strengthening on Zona Karst of Seropan Cave Walls

Sulha Sulha¹*, Ahmad Rifa’i², Minson Simatupang¹, Umran Sarita¹
¹Department of Civil Engineering, Universitas Haluoleo, 93232 Kendari, Sulawesi Tenggara, INDONESIA
²Program Studi Teknik Sipil, Universitas Gadjah Mada, Jln. Grafika No. 2 Kampus UGM Yogyakarta, 55281, INDONESIA

*Corresponding author’s e-mail: sulha@uho.ac.id

Abstract. The Indonesian state has many caves in several regions with unique legends and high cultural values, including Sang Hyang Sirah Cave in West Java, Seropan Cave and Semar Cave in Central Java, Liangkabori Cave on Muna Island and others. Seropan Cave has a large potential of water resources, especially in the karst area in the form of water flows in underground rivers. This study aims to analyze strain stress that occurs due to karst conditions on variations in groundwater level. Analysis method used finite element and plan strain model with the help of Plaxis v8.6 Software. The analytical approach is performed on the appearance of the cave with normal water level conditions, flood water levels and extreme use of shotcrete reinforcement, rock bolt and a combination of both. Material properties at the location are taken from the results of research and testing of the Seropan Cave IWRM laboratory and UGM Technical Team. The simulation results show that the existing conditions require wall reinforcement. Wall reinforcement uses 7 cm thick shotcrete and rock bolt with a diameter of 2 cm 4 m long with the distance between rock bolt is 2 m. Strengthening combination of rock bolt and shotcrete gives the highest safety factor of 2.01 while in earthquake conditions, it reaches 1.76. Combination wall reinforcement is quite stable against static and dynamic loads.

1. INTRODUCTION

Cai, M. (2011) examined the characteristics of rock mass by considering the diversity of rock properties for the design of large tunnels and caves. He conducted a quantitative, probabilistic approach using the Geological Strength Index (GSI) system to characterize rock masses. He said that this method provided a theory of a systematic analysis approach to the uncertainty of rock mass characteristics, and this can help us to know the part of knowing how uncertainty arises and how to decide the design of rock support systems that might be affected by it.

The structure of some caves cannot be avoided against unsafe and unstable conditions. This provides uncertainty, which results in the construction process becoming complicated and increasing risk. Therefore, the development of efficient scientific steps to ensure the quality and safety of construction projects are very important (Bao Jin at all, 2015).

Deng Hongling et all. (2015) examined the dynamic response of tunnels through karst caves to impact loads. Merela reported that the tunnel was only destroyed when it received a collision load of not less than 0.1 seconds, a vertical displacement of 2.88 m, a horizontal displacement of 0.80 m. The tunnel falls when the rock mass is destroyed at a maximum impact of 7E + 6 KN on the tunnel.

In this study, estimates of rock mass properties are based on GSI values using Rocklab software. The support system used based on rock mass classification RMR (Bieniawski, 1989). Based on the determined rock mass and support system, numerical simulations are carried out using Plaxis software to estimate the stability of the cave wall. The cave code that is located on karst land is important for stability analysis on static and dynamic loads.
2. STRENGTHENING OF THE CAVE WALL

2.1. Criteria for Rock Failure

The collapse criteria are based on Hoek-Brown 2002 as follows:

\[
\sigma'_{cm} = \sigma_{ci} \frac{(m_\alpha + 4s - a(m_\alpha - 8s)(m_\alpha + s)^{a-1})}{2(1+a)(2+a)}
\]

(1)

\[
m_\alpha = m_\alpha \cdot \exp \left( \frac{GSI - 100}{28 - 14D} \right)
\]

(2)

\[
m_i = \frac{\sigma_{ci}}{\sigma_{ct}}
\]

(3)

\[
s = \exp \left( \frac{GSI - 100}{9 - 3D} \right)
\]

(4)

\[
a = \frac{1}{2} + \frac{1}{6} \left( e^{-GSI/15} - e^{-20/3} \right)
\]

(5)

where \( \sigma_{ci} \) is rock compressive stress from the UCS test (MPa), \( \sigma_{ct} \) is tensile stress of the point load test (MPa), \( m_i \) is compressive stress ratio and tensile stress ratio, \( m_b \) is reduction of \( m_i \) value, \( s \) and \( a \) are rock mass constants, \( GSI \) is geological stress index based on fracture arrangement and surface conditions \( D \) is disturbance factor during excavation.

For estimating \( GSI \), \( D \) values and determine rock shear strength based on Hoek-Brown 2002 criteria. Analysis of software approach to soil and rock is generally based on Mohr-Coulomb criteria, so an approach is needed from the Mohr-Coulomb equation \((c, \phi)\) with the Hoek-Brown criteria, namely:

\[
\phi' = \sin^{-1} \left[ \frac{6am_b(s+m_b\sigma'_{3n})^{-1}}{2(1+a)(2+a)+6am_b(s+m_b\sigma'_{3n})^{-1}} \right]
\]

(6)

\[
c' = \frac{\sigma_{ci}[(1+2a)s+(1-a)m_b\sigma'_{3n}]^{s+m_b\sigma'_{3n}}^{a-1}}{(1+a)(2+a)\sqrt{1+\left(6am_b(s+m_b\sigma'_{3n})^{-1}\right)^{a-1}/((1+a)(2+a))}}
\]

(7)

where \( \sigma'_{3n} = \sigma_{3\text{max}}/\sigma_{ci} \)

2.2 Rock Mass Classification

The technical properties of rock mass can be obtained from the classification of rock mass. The classification aims to estimate the strength of the rock mass according to the type and class of rock and the permanent support system to be used. To estimate rock mass, rock classification can be used the RMR criteria. There are six basic parameters used in the RMR system (Bieniawski, 1989), namely: Intact rock strength test, which is based on index point load or uniaxial compressive strength, Rock Quality Designation (RQD), discontinuous field spacing and conditions, water condition’s soil and disjointed plane orientation. The total RMR weight from the six parameters above is used to determine the rock mass classification and the support system to be used. The support system used is determined according to Table 1.

2.3. Safety Factor

According to Terzaghi and Peck, (1967) and the Canadian Geotechnical Society, (1992), shear failure for soil retaining structures was 1.5-2 as in table 2. Safe factor analysis of collapse in PLAXIS, using the Phi-c reduction method which principally refers to the Coulomb criteria with the following equation:

\[
\frac{c}{c_{cr}} = \left( \frac{\tan \phi}{\tan \phi_{cr}} \right) = \Sigma M_{sf}
\]

(8)
Table 1. The procedure for determining supporting systems is based on value of the RMR (Bieniawski, 1989).

| Rock mass class          | Excavation                        | Rock bolts (20 mm diameter, fully grouted) | Shotcrete                        | Steel set         |
|--------------------------|-----------------------------------|--------------------------------------------|----------------------------------|-------------------|
| I-Very good rock RMR. 81 – 100 | Full face, 3 m advance.           | Locally, bolts in crown 3 m long, spaced 2.5 m with occasional wire mesh | Generally no support required except spot bolting | None              |
| II-Good rock RMR. 61 – 80 | Full face, 1 – 1.5 m advance, complete support 20 m from face | Systematic bolts 4 m long, spaced 1.5-2 m in crown and walls with wire mesh | 50 – 100 mm in crown and 30 mm in sides | None              |
| III-Fair rock RMR. 41 – 60 | Top heading and bench 1.5 – 3 m advance in top heading. Commence support after each blast. Complete support 10 m from face. | Systematic bolts 4-5 m long, spaced 1-1.5 m in crown and walls with wire mesh | 100-150 mm in crown and 100 mm in sides | Light to medium ribs spaced 1.5 m where required. |
| IV-Poor rock RMR. 21 – 40 | Top heading and bench 1.0 – 1.5 m advance in top heading. Install support concurrently with excavation, 10 m from face. | Systematic bolts 5-6 m long, spaced 1-1.5 m in crown and walls with wire mesh, bolt invert. | 150-200 mm in crown, 150 mm in sides, and 50 mm on face | Medium to heavy ribs spaced 0.75 m with steel lagging and forepoling if required. Close invert. |
| V-Very poor rock RMR. < 20 | Multiple drifts 0.5 – 1.5 m advance in top heading. Install support concurrently with excavation. Shotcrete as soon as possible after balancing. | Systematic bolts 5-6 m long, spaced 1-1.5 m in crown and walls with wire mess, bolt invert. | 150-200 mm in crown, 150 mm in sides, and 50 mm on face | Medium to heavy ribs spaced 0.75 m with steel lagging and forepoling if required. Close invert. |

Table 2. The minimum SF for shear failure according to Terzaghi and Peck, (1967) and the Canadian Geotechnical Society, (1992) in Wyllie and Mah, (2005).

| Failure type | Category                              | Safety factor |
|--------------|---------------------------------------|---------------|
| Shearing     | Earth works                           | 1.3 – 1.5     |
| Earth retaining structures, excavation |                          | 1.5 – 2.0     |
| Foundation   |                                       | 2 – 3         |

3. NUMERICAL SIMULATION

3.1. Finite element method in Plaxis

The modeling of the cave wall following procedure is the generation of initial stress by K_o procedure, determine of water level, activate surcharge load, installation of shotcrete, activate of rock bolts and earthquake load.

3.2. Research Procedures

The characteristics of the Seropan cave soil / rock structure are based on the results of the research report and the Seropan Cave IWRM laboratory test and UGM Technical Team and the results of Seropan cave lay out measurements. The loading and condition of the river water level to determine the behavior and displacement tendencies and stresses that occur due to static or dynamic loading. The simulation results obtained a safe and stable reinforcement method to be recommended at the repair stage in the field.

From the results of research and testing of Seropan Cave material in the laboratory of the Faculty of Engineering UGM, the rock mass was in the third class category (fair rock class) with an RMR = 53. The reinforcement method was in accordance to the guidelines of Bieniawski in 1989, in the form of rock bolt with a depth of 4 m and an average distance of 1.5-2 m. In addition, shotcrete needs to be added with a thickness of 50-100 mm on the crown and 30 mm in the cave wall. Taking into account the dynamic load, thick shotcrete is used 70 mm for the entire surface of the cave wall. RocLab software
can be used as an alternative determination of shear strength. Based on the RocLab software approach, obtained output data in the form of cohesion \((c) = 0.158 \text{ MPa}\), friction angle in rock \((\varphi) = 39.72^\circ\), and rock elasticity \((E_m) = 210.32 \text{ MPa}\) based on Hoek-Brown 2002 criteria.

The rock mass classification in this case is moderate (rock fair). The reinforcement method is in accordance to the guidelines of Bieniawski in 1989, in the form of rock bolt with a depth of 4 m and an average distance of 1.5-2 m. In addition, shotcrete needs to be added with a thickness of 50-100 mm on the crown and 30 mm on the cave wall. Taking into account the dynamic load, thick shotcrete is used 70 mm for the entire surface of the cave wall of the foundation construction area. Recapitulation of PLAXIS input data for each geometry model is presented in table 3.

Topographic measurement results in the form of layouts and cross sections of the initial design of the foundation to be analyzed are presented in Figure 1a. The Seropan underground river is located at a depth of about 70 meters below the soil surface. The dimensions of geometry modeling are (55,60) meters. The upper rock layer from the ground surface to a depth of 42.77 meters is considered as a uniform load. The amount it is taken from the weight of the rock unit multiplied by the height of the rock, amounting to 780 kNm\(^{-2}\). The modeling used is plane strain, where Seropan cave is a non-irregular and oval-shaped non-tunnel. The existing condition of Seropan cave and observation point is modeled as in Figure 1b. To calculate the dynamic load, in the stability analysis of the cave wall uses a numerical constant which is usually called the earthquake coefficient \((k_g)\). This coefficient is given in percent of gravity such as the 10% gravity coefficient (0.1g). According to the 2017 earthquake source map of Indonesia, Yogyakarta region has the earthquake acceleration coefficient of 0.3 - 0.4g.

3.3. Effect of water level fluctuations

There are three variations in the regulation of groundwater level, which are reviewed, namely normal water level was 0.92 meters. Flood water level was 1.92 meters and maximum (extreme) flood water level as high as 17.72 meters. Calculation of water pressure (generate water pressure) is done by defining the groundwater conditions (phreatic level) on the model geometry, so that the calculation of water pressure can be carried out. For flood water levels and extreme steps taken with the normal water level, the only difference is the water level. The relationship between the increase in total displacement and the safe number of construction stages in different river water conditions can be seen in Figure 2a.

3.4. Displacement and Safety Factors

To get the results of the analysis, the displacement value is observed at a certain point. This point is a part of the cave wall that experiences the largest displacement. Observation points are placed on the surface of the cave wall that is Point A, B, C and D according to Figure 1a. Based on the results of numerical simulations, a safe factor and displacement value is obtained for each construction stage in accordance with Figure 2b.

| Parameters                                      | Symbols | Value | Unit |
|-------------------------------------------------|---------|-------|------|
| Material model                                  | -       | Mohr  | -    |
| Type of material behavior                       | -       | Tak   | -    |
| Weight of rock content above the phreatic       | \(\gamma_{unsat}\) | 18,37 | kNm\(^{-3}\) |
| Weight of rock content below the phreatic       | \(\gamma_{sat}\) | 19,28 | kNm\(^{-3}\) |
| Horizontal direction permeability               | \(k_x\) | 0,000 | ms\(^{-1}\) |
| Vertical direction permeability                 | \(k_y\) | 0,000 | ms\(^{-1}\) |
| Young's Modulus                                 | \(E_{ref}\) | 210,3 | kNm\(^{-2}\) |
| Poisson's ratio                                 | \(\nu\) | 0,25  | -    |
| Cohesion                                        | \(c_{ref}\) | 158   | kNm\(^{-2}\) |
| Friction angle                                  | \(\varphi\) | 39,72 | ⁰    |
| Dynamic friction angle (\(\varphi - 2\) ⁰)     | \(\varphi_{din}\) | 37,72 | ⁰    |
| Dilatancy angle                                 | \(\psi\) | 3 ⁰   |      |
| The interface shear strength reduction          | \(R_{inter}\) | 0,52  |      |
Figure 1. (a) Cross section, the dimensions and the observation points of the cave wall (b) Modeling the existing condition of the cave.

Figure 2. (a) Chart relationship of the total displacement to water level conditions, (b) Chart relationship of safety factor in each of strengthening with different water level conditions.

Figure 3. (a) Displacement chart on the cave wall at the observation points, (b) Chart relationship of safety factor to loading at each stage of construction.

From the picture above shows that the installation of a combination support system results in a decrease in displacement values of the cave wall. The safe factor after installing a support system against the collapse of the cave due to earthquake load with base rock acceleration of $350 \text{ cm/s}^2$ is reached 1.76. Rock bolt and shotcrete combination can reduce displacement and significantly increase the safe factor.
of the cave wall against static and dynamic loads. It can be applied in the maintenance and development
stages of the cave in that location.

4. CONCLUSION
The location of the study included in the category of fair rock. The reinforcement method used rock
bolt with a length of 4 m. The distance between rock bolt is 2 m and thickness of shotcrete are 70 mm.
Installation of rock bolt and shotcrete support system results in a decline displacement of the cave wall.
The rock bolt and shotcrete support system used in this study are strong enough to support earthquake
loads below 350 cms².

REFERENCES
[1] Bieniawski, Z.T., 1989, Engineering Rock Mass Classifications, John Wiley and Sons. New York.
[2] Cai, M., 2011, Rock Mass Characterization and Rock Property Variability Considerations for
Tunnel and Cavern Design, Rock Mechanics & Rock Engineering, 44 Issue 4, 379-399,doi
10.1007/s00603-011-0138-5.
[3] Deng Hongliang at all, 2015, The dynamic response of tunnel through the Karst cave under
impact load, Applied Mechanics & Materials., 777, 135 – 142, doi 0.4028 / www.scientific.net
/AMM.777.135
[4] Geotechnical Engineering Office, 2006, Foundation Design And Construction, Geo Publication
No. 1, 2006.
[5] Hoek, E., 2002, Hoek-Brown Failure Criterion, Program“RocLab”, http://www.rockscience.com,
27 Maret 2013.
[6] Irsryam, M. at all, 2017, Peta Sumber Bahaya Gempa Indonesia Tahun 2017, Pusat Penelitian
dan Pengembangan Perumahan dan Permukiman.
[7] Jin Bao, Zhang Hongjun dan Jianyang Zhang, 2015, A new Technique for construction of limestone
cave, Key Engineering Materials, 648, 9 – 16, doi 10.4028 / www.scientific.net /KEM.648.9
[8] National Earthquake Study Center, 2017, Indonesian Earthquake Source and Hazard Map of 21017,
Housing and Settlement Research and Development Center, Research and Development
Ministry of Public Works and Public Housing, Bandung.
[9] Rifa’i, A., 2011, Survey and Test of Soil Seropan Underground Mechanics Soil Laboratory
Laboratory Phase I in Gunung Kidul Regency, Faculty of Engineering Department of Civil
Engineering and Environmental Soil Mechanics Laboratory, Gadjah Mada University,
Yogyakarta.
[10] Wyllie, D.C. and Mah, C.W., 2005, Rock Slope Engineering, Spon Press Taylor & Francis Group,
London and New York.