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Geological and Geotechnical Assessment in Support of the Protection of the Indigenous Peoples Religious Practices affected by a Water Dam Project

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ABSTRACT

Geological and geotechnical assessment, as well as technical support by way of structural analysis, were carried out to ensure the safe transfer of a boulder with a regularly shaped dark clast, which a group of indigenous people considers as a religious artifact. The huge rock is located at an area that is expected to be inundated once a water dam project starts regular operation. Thus, it is necessary that the rock be relocated at a higher ground to prevent it from being submerged thereby permitting the locals to continue their religious practice. The boulder is irregularly shaped whose mass is estimated to be within 11.5 to 12.5 tons, and is composed of highly-indurated agglomerate with a tuffaceous matrix. Based on the estimated intact rock strength, the rock is deemed to be highly durable. Slope stability analysis, via Limit-Equilibrium Method, and settlement analysis were carried out to assess the safety of the seven prospect sites. Of the seven sites, Site 5 was found to be the most ideal—both in terms of safety and practicality. Structural analysis was also carried out for the steel systems used for the relocation. The rock was safely transferred to Site 5 after confirming structural soundness and after reviewing the method statement and equipment specifications. The paper discusses the results of the geological and geotechnical assessment for the site, as well as the modeling and analysis done to support the methodology of transfer, ensuring the protection of the indigenous peoples right to practice their religion.

Keywords: indigenous people, geological and geotechnical assessment, slope stability, boulder relocation, dam

1 INTRODUCTION

Over the last few years, major infrastructure development in the Philippines has played a huge role in its economic management as part of its "*Build! Build! Build!*" Program that started in 2017. One particular project is the construction of a new Bulk Water Supply (BWS) system in Rizal, Philippines that can deliver 518 million liters per day (MLD) of water to Metro Manila. The proposed BWS project comprises of pump stations, weirs, tunnels, and a large water supply dam. Along the channel connecting the pump station (upstream) to the dam structure (downstream) lies the "*Sacred Stone*"—a huge boulder with a regularly shaped dark clast (Figure 1).

Local indigenous people consider the Sacred Stone as a religious article, and as such, hold it in high regard and revere it with the utmost veneration. However, the area is expected to be inundated once the BWS project starts regular operation. Moreover, it is necessary that the Sacred Stone be relocated at a higher ground to prevent it from being submerged—thereby permitting the locals to continue their religious practice without complications.

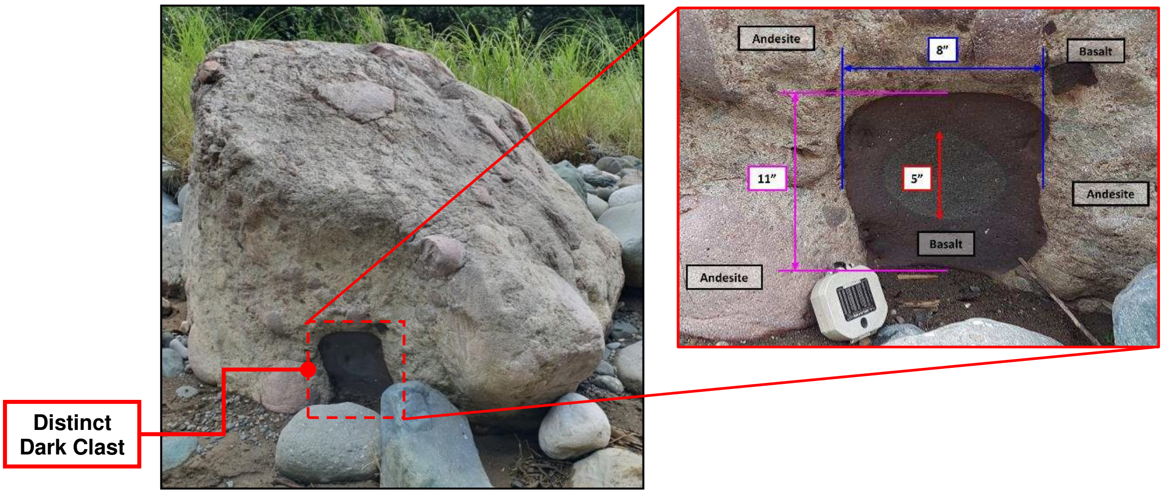

Figure 1. *The Sacred Stone (viewed from up front)*

For this purpose, a geological and geotechnical assessment of the Sacred Stone, itself, and seven prospect relocation sites was conducted with the following objectives:

- To characterize the Sacred Stone and verify its capacity to withstand mechanical disturbances;
- To estimate the rock's volume and gross mass;
- To assess the site and its vicinity in terms of accessibility for equipment deployment;
- To establish recommendations for equipment specifications and come up with a feasible relocation methodology—from lifting the rock to its current position, to protecting it from possible damages, and eventually unloading it to a viable relocation site; and
- To assess the plausible geohazards of possible relocation sites.

2 CHARACTERIZATION OF SACRED STONE

2.1 Regional Geology

Looking at Figure 2 (Mines and Geosciences Bureau/MGB, 1983), the Cretaceous Kinabuan Formation (KF) directly underlies the Sacred Stone. The Kinabuan Formation is comprised of basaltic flows, breccia, greywacke, highly-indurated sandstone, shale, and/or chert (MGB, 2004). However, it seems like the characterization of the Sacred Stone differs from the composition of the Kinabuan Formation. It can then be inferred that the Sacred Stone was not formed in-situ and is probably a transported boulder whose composition is closer to the Miocene Madlum Formation (MF) found further upstream of the Tayabasan River. The Madlum Formation is comprised of andesitic to basaltic flows, greywacke, shale, agglomerate, conglomerate, tuff, argillite, limestone, and calcareous sandstone (MGB, 2004).

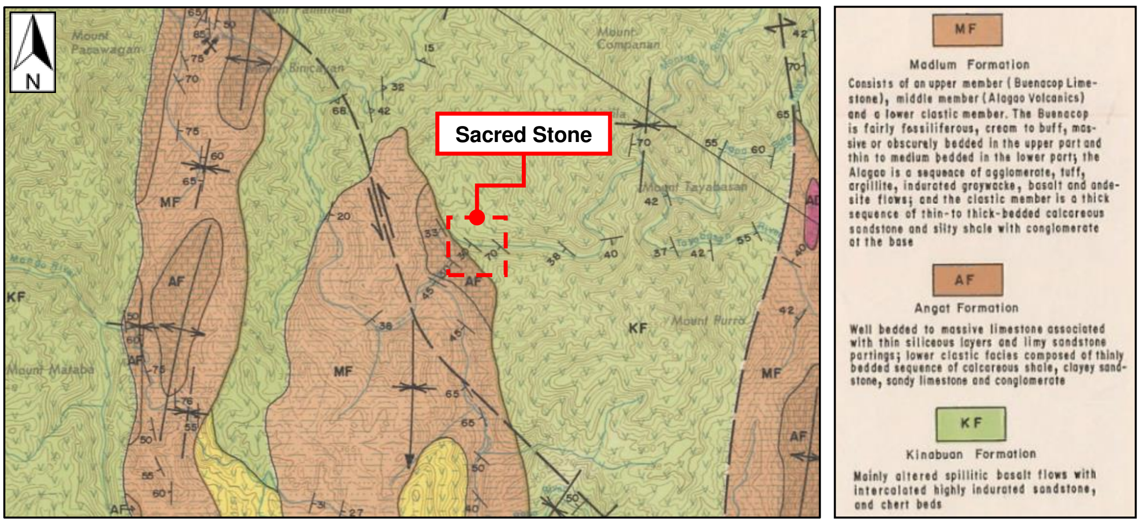

Figure 2. *Extract from the 1:50,000 Geological Map of Montalban Quadrangle (Source: MGB, 1983)*

2.2 Geologic Composition and Surface Conditions

The Sacred Stone is an irregularly shaped boulder composed of highly-indurated agglomerate. It has a tuffaceous matrix, enclosing light to purplish colored sub-rounded cobbles and boulders of basalt and andesite. As shown in Figure 1, it has a particularly dark-colored basalt clast that closely resembles a regularly shaped rectangle whose dimensions are approximately 8 inches by 11 inches. There is also a distinct shift in color (to gray), resembling a regular 5-inch diameter circle, positioned practically at the center of the rectangle. These astonishingly remarkable features are two (2) of several reasons as to why the locals consider the stone to be sacred.

Moreover, its base is partially buried in moist granular soil, possibly due its location being frequently submerged over the past few days/weeks. However, despite the high exposure to weathering elements, most of the rocks on-site are still mostly intact with no observed friable portions. It is also worth mentioning that there are also several isolated hairline cracks scattered throughout the Sacred Stone's surface. Nevertheless, none of these were observed to be persistent or even wide enough to propagate through the interior and break the stone entirely into smaller parts upon experiencing stress.

Figure 3. *Surface conditions of the Sacred Stone*

2.3 Volume and Mass

Due to the Sacred Stone's irregular shape, drone shots were taken to generate a 3D model of the Sacred Stone's surface. The volume is estimated to be 3.57 m^3, which is much less than the initial conservative estimate of 6 cu. meters. However, due to uncertainties, a safety factor of 1.25 was applied for prudence—leading to an estimated volume of 4.5 m^3. In the absence of actual laboratory testing for rock density or unit weight, typical unit weight values for conglomerate, agglomerate, and andesite were utilized—resulting to the design mass range of 11.5 to 12.5 tons for the given volume.

2.4 Rock Strength

Methods to test the rock strength of the Sacred Stone were also limited due to restrictions imposed by the local community. As a compromise, a relatively smaller sample of the same rock type, with similar properties, and located just a few meters away from the Sacred Stone was tested using the 1975 Burnett technique (British Standard 5930, 1981) for estimating intact rock strength. The test involves striking the sample using a drifting geological hammer and observing the sample's condition and soundness after impact. Based on the response of the sample, an assessment can be made to get an indicative idea of the intact rock strength of the sample. Table 2 presents the matrix developed by Burnett in 1975.

Table 2. *Matrix for estimating intact rock strength by simple means*

Intact rock strength (MPa)	Response from "simple means" test (using a standard 1-kg geological hammer)
< 1.25	crumbles in hand
1.25 - 5	thin slabs break easily in hand
5 - 12.5	thin slabs break by heavy pressure
12.5 - 50	lumps broken by light hammer blows
50 - 100	lumps broken by heavy hammer blows
100 - 200	lumps only chip by heavy hammer blows
> 200	rocks ring on hammer blows; sparks fly

The simple means test revealed that the identical rock sample, may have an estimated strength ranging from 100 MPa to 200 MPa. While a ringing sound was observed after being hit with a geological hammer, very minor chipping was observed post-impact. In any case, the Sacred Stone is deemed to be in a good enough condition for relocation. In other words, cracking, crumbling, and fracturing are not outstanding concerns for the Sacred Stone except if, during the relocation process, the stone somehow either falls from a great height, or if it topples and rolls downslope continuously.

3 RELOCATION SITE ASSESSMENT

3.1 Site Locations

Initially, the local indigenous group identified their own ideal relocation site, within the permitted area of relocation, based on accessibility. This initial prospect relocation site is 1.0 km away from the Sacred Stone, currently has a sloping terrain of around 20 degrees, and is about 235 meters higher than the original position of the Sacred Stone in terms of elevation. Aside from this initial target relocation site, six additional prospect sites are selected from available topographic data and drone shots. The location map of the proposed relocation sites is shown in Figure 4. The selection of the prospect relocation sites is based on the following criteria:

a) the relocation site should be high enough to avoid being inundated in case of maximum flood level (presented in Figure 4 as blue lines)
b) slope instability will not be an issue; and
c) the terrain should be relatively flat because it will serve as a permanent, natural platform where the locals can continue pursuing their religious practices.

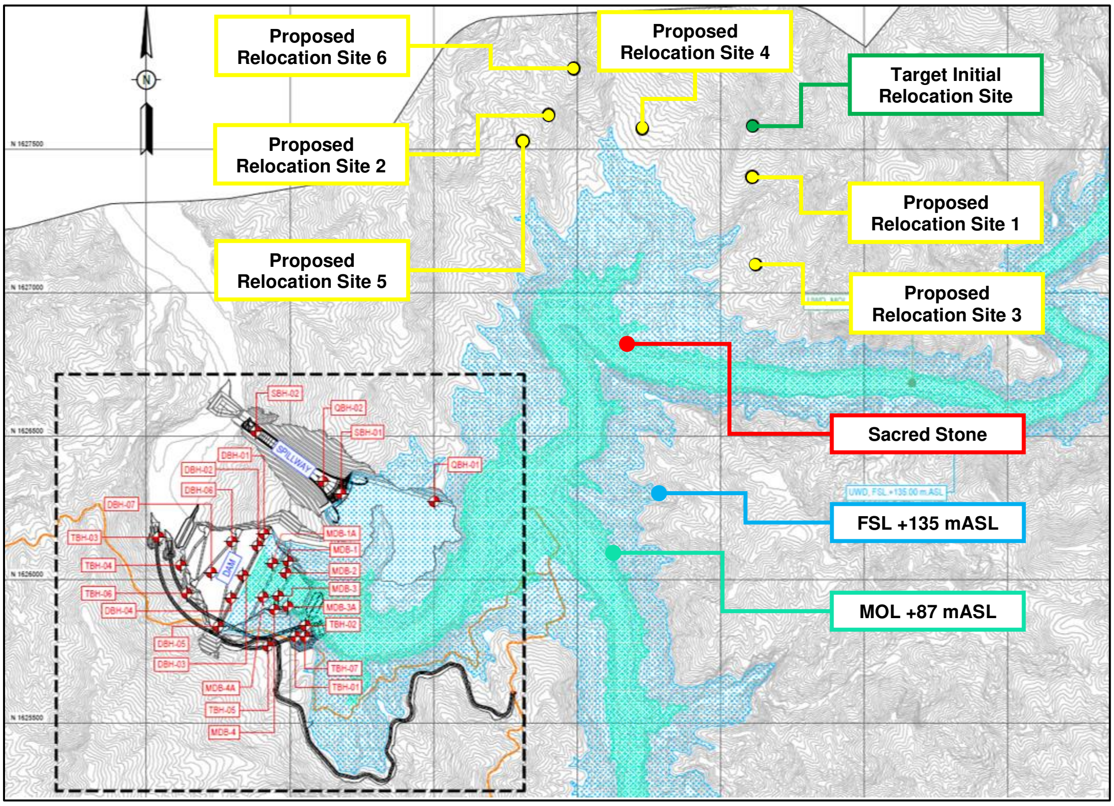

Figure 4. *Location map of proposed relocation sites*

Based on the design of the dam structure, the Minimum Operating Level (MOL) is at 87 meters above sea level (mASL) while the Full Supply Level (FSL) is at 135 mASL. The vertical offset of the elevation of each relocation site from these levels are also summarized in Table 2.

Table 2. *Proposed Relocation Sites*

Relocation Site	Elevation (mASL)	Vertical Offset (m)	
		MOL	FSL
Initial Location	303	216	168
Proposed Location 1	221	134	86
Proposed Location 2	228	141	93
Proposed Location 3	186	99	51
Proposed Location 4	166	79	31
Proposed Location 5	211	124	76
Proposed Location 6	244	157	109

3.2 Slope Stability Analysis

Slope stability is the potential or likelihood of a slope to fail due to a specific mechanism. It involves the interplay of two types of forces: a) driving forces which promote the downward movement of materials; and b) resisting forces which defer the downward movement of materials. Typical causes of slope failures are earthquakes, geologic features, induced loads, rainfall, and erosion.

In this study, slope stability analysis was carried out using the Limit-Equilibrium Method (LEM). In LEM, the mass is divided into small slices along an assumed or known failure surface, as shown in Figure 5. Forces that are acting on each slice such as weight, normal and tangential reactions, and shear forces are determined. In this study, both circular and non-circular slope stability analyses were carried out in Rocscience Slide 6.0 using the GLE/Morgenstern-Price method. The method is generally applicable to all slope geometries and soil profiles. In this method, it is assumed that the shear forces between slices are related to the normal forces. Moreover, the location of the normal force on the base of the slice is assumed to be at the center, and the stresses are integrated across each slice.

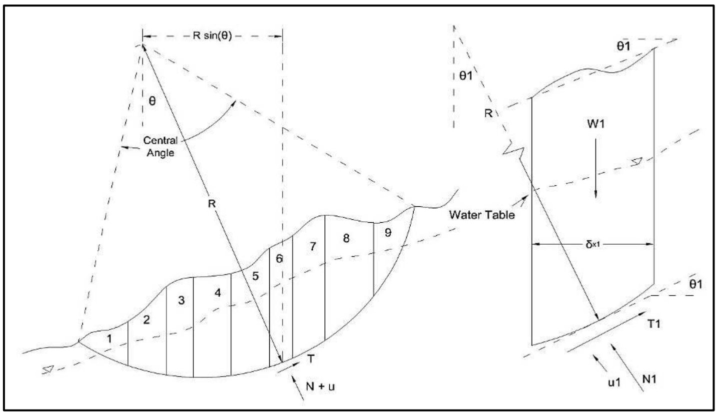

Figure 5. *Slope Stability Analysis by Limit-Equilibrium Method*

3.2.1 Subsurface model

From the Geological Investigation (GI) data, the soil cover around the area of the proposed relocation sites is characterized as quaternary colluvial and alluvial deposits that is about 8 meters mid-slope and practically negligible at the riverbed (generally increases with elevation). Moreover, borehole data suggests that the upper 4 meters is comprised of loose to medium dense granular material, whereas the lower 4 meters, while still classified as medium dense, is more competent. The estimated Mohr-Coulomb shear strength parameters shown in Table 3.

Table 3. *Mohr-Coulomb shear strength parameters of soils*

Depth (m)	Description	SPT N-Value	Relative Density	Color	γ_{dry} (kN/m^3)	γ_{wet} (kN/m^3)	c (kPa)	ϕ (°)
0 - 4	Sands	15 - 19	Med. Dense		16	17	5	31
4 - 8	Silty Sands	24 - 29	Med. Dense		17	18	7	33

where γ_{dry}, γ_{wet}, c, ϕ are the dry and saturated unit weights, cohesion, and friction angle of the idealized soil layers.

Furthermore, the rock formation is found beneath the residual soil cover and is characterized as alternating layers of sandstones and mudstones. The upper rock layers are moderately to highly weathered with low Rock Quality Designation (RQD) values, whereas the lower rock layers are fresh to slightly weathered with high RQD values. The rock samples tested from various boreholes were utilized to determine the idealization of rock layers as shown in Table 4. In the mathematical model, the rock layers are modeled using the Hoek-Brown model, wherein the Uniaxial Compressive Strength (UCS) and Rock Mass Modulus of Elasticity (E_{rm}) are averaged according to the idealized layering.

Table 4. *Hoek-Brown parameters of rocks*

Depth (m)	Description	Color	γ_{dry} (kN/m^3)	γ_{wet} (kN/m^3)	UCS (MPa)	GSI	m_i	E_{rm} (GPa)
8 - 78	Sandstone & Mudstone		25	26	13.7	45	13	1.7
78 - 138					19.8	50	17	2.6
138 - 160					40.0	55	21	4.0

where GSI is the Geological Strength Index and m_i is the intact core modulus of the rock layers. The rock parameters presented above were provided by the Designer of the dam structure.

3.2.2 Loading conditions

In this study, a 60-kN/m vertical point load is adopted to represent the weight of the Sacred Stone. The point load is applied at multiple locations along the slope representing the Sacred Stone's different positions during the actual transfer. This approach is a simplification of the moving load scenario.

When considering seismic loading for slopes, a pseudo-static condition is typically idealized, wherein constant seismic coefficients (k_h is the horizontal seismic coefficient) are taken as fractions of the Peak Ground Acceleration (PGA). The pseudo-static method is the simplest and most common method in evaluating the stability slopes during earthquakes. In the Philippines, it is common practice to adopt a horizontal k_h value as half of the surface PGA, which is primarily based on the work done by Hynes-Griffin and Franklin (1984) and Kavazanjian et al. (1997).

The PGA is further estimated from a hypothetical rupture scenario of the West Valley fault (WVF), which is said to be able to produce a moment magnitude (M_w) 7.2 earthquake, located about 10 km west of the site, using the NGA-West2 attenuation models developed by the Pacific Earthquake Engineering Research Center (PEER) in 2008 and later modified in 2014. Based on the proximity of the proposed relocations sites to the WVF, the expected surface PGA is estimated to be 0.45g, which was adopted in the analysis. The four (4) of the attenuation models utilized in the study are:

- Abrahamson, Silva, and Kamai (ASK14)
- Boore, Stewart, Seyhan, and Atkinson (BSSA14)
- Campbell and Bozorgnia (CB14)
- Chiou and Youngs (CY14)

3.2.3 Design scenarios

When carrying out slope stability analysis via LEM, equilibrium conditions must always be met. Instability is caused when these conditions are violated. In other words, stability assessment shall be based on the interplay between the driving and resisting forces that act on the supposed failure surface. The Factor of Safety (FS) is expressed as the ratio of resisting forces to the driving or overturning forces.

The main objective is to determine if the relocation site slopes are at risk of instability. An FS value below unity (1.0) is an indicator of impending instability. However, inspection of the critical slip surface should also be done prior to concluding slope instability because some critical slip surfaces may also just be erosion. Table 5 presents the scenarios analyzed in this study and their respective conditions.

Table 5. *Global slope stability analysis scenarios*

Case	Water Level	Porewater Pressure Ratio, r_u	Seismic Coefficient, k_h
1) Long-term, static	MOL and FSL	0	0
2) High porewater pressure, static	FSL	*varying*	0
3) Earthquake (pseudo-static)	FSL	0	0.225

Case 1 considers the condition where there is no soil saturation due to rainfall and no earthquakes. Both operating water levels (MOL and FSL) were considered in Case 1 (1A and 1B) for comparison.

For Case 2, only the FSL is considered for the no-earthquake condition. However, in this case, the saturation of soil due to rainfall is already applied. This is because high-intensity rainfall is expected to happen several times a year considering the climate of the Philippines. Conditions wherein porewater pressure build-up becoming quite excessive is therefore plausible. The porewater pressure ratio, r_u, is defined as the fraction of pore water pressure to the total vertical pressure exerted by soil. This ratio represents the saturation level of the soil mass in case of a rainfall event. For Case 2, the r_u values 0.15, 0.30, and 0.40 would simulate a soil condition of varying saturation, with the uppermost soil layer having the largest r_u value.

The last case, Case 3, also considers only the FSL for the no rainfall or unsaturated condition. However, an additional loading due to earthquake is applied. Aside from the static lateral earth pressure due to the surrounding soils, earthquakes can also induce considerable destabilizing inertial forces. Seismic loads permanently degrade the effective shear strength of the soil mass due to the stress and fatigue resulting from the prolonged exposure to cyclic loading. Seismic analysis is therefore essential when evaluating the stability and deformation especially in seismically-active regions/countries like the Philippines.

3.2.4 Slope stability analysis results

The results for Cases 1A and 1B are similar for all proposed relocation sites. The values of the minimum FS obtained in Cases 1A and 1B suggest that the slopes around the vicinity of all sites are generally stable when there is no rainfall and no earthquake.

The least factors of safety were observed in Case 2 for all sites which means that the saturation of soil due to heavy rainfall is the most critical condition for failure of the slopes. The closest distance where local slope failure may occur is 60 meters up-slope from the Initial Prospect Site and 60 meters up-slope from the Proposed Site 1.

When considering earthquakes, local slope failure was observed in all cases. The closest failure surfaces are 15 to 60 meters away from the proposed relocation sites except for Proposed Sites 2 and 5 where slope failure occurs at relatively farther distances of 150 and 100 meters, respectively. Figure 6 below presents the LEM result of Prospect Site 5 under pseudo-static conditions.

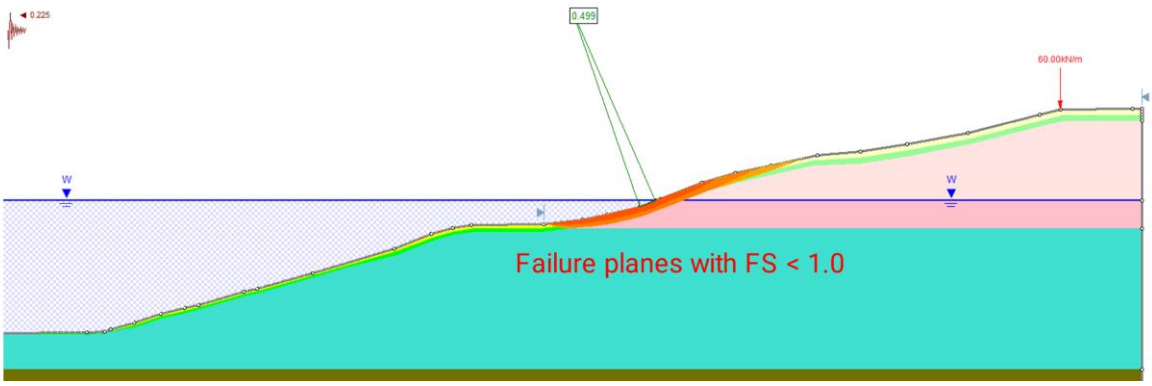

Figure 6. *Sample LEM result of Prospect Site 5 under pseudo-static conditions (FS_{min} = 0.499)*

Considering the results of the slope stability analysis, the most ideal relocation sites would be at Proposed Sites 2 and 5. Aside from their relatively flat terrain, the surrounding slopes up-slope and down-slope are also stable. In addition, Proposed Site 4 may also be a good relocation point because the nearby slopes are stable in dry and static conditions, and it has the least vertical climb from the current location of the Sacred Stone. However, there is risk of erosion 35m up-slope during earthquake. Ultimately, Proposed Site 5, situated about 130 meters above the Sacred Stone, was selected as the final relocation spot, which was also approved by the local indigenous group.

3.3 Settlement Analysis

Settlement refers to the vertical displacement of the soil due to foundation or other loads causing change in stress that compress the soil layer. In general, soil settlement may be divided into three categories: (1) elastic (or immediate) settlement, caused by elastic deformation of soil without change in moisture content; (2) primary consolidation (long term) settlement, which is the result of volume change in cohesive soils because of expulsion of water; and (3) secondary consolidation settlement, which is the result of the plastic adjustment of soil fabrics in cohesive soils.

Since the soil cover around the proposed relocation sites are primarily made of granular material, only the immediate settlement of soil under the relocation point is of concern upon the transfer of the Sacred Stone. Settlement analysis was carried out using Rocscience Settle3D—a software program for the analysis of vertical consolidation and settlement under foundations, embankments, and surface loading.

From the analyses, the maximum anticipated immediate settlements for all relocation sites are all less than 5 mm. Thus, it is expected that no excessive soil settlement will occur at the location where the Sacred Stone post-relocation.

4 RELOCATION PROCESS

With the final relocation site identified, a Contractor was engaged to carry out the earthworks (for the access road), the lifting, and the transfer itself. In order to ensure a safe and orderly relocation process, the proposed methodology and material specifications were also reviewed.

4.1 Structural assessment

The proposed methodology involved constructing a makeshift steel cage-sled system (Figure 7) that will be tied to the back of a backhoe and dragged up-slope through an access road until reaching Proposed Site 5 (Figure 8). The Sacred Stone was also proposed to be lifted by a backhoe (lifting capacity of around 20 tons) onto the sled, and out of it after reaching the destination. Prior to lifting the Sacred Stone onto the sled, the Sacred Stone shall first be secured onto a steel cage frame welded on-site to ensure that the fit is not loose and properly snugged in.

As the main objective of this study really is for geological and geotechnical assessment, the specific calculations of the structural review/analysis will not be detailed in this paper. However, to give an idea of what was inspected, it is the structural capacities of the makeshift sled, the equipment (backhoe, hooks, shackles), as well as the slings/straps used to tie the components together that were evaluated based on the estimated mass and size of the Sacred Stone. In the review of the structural capacities, attention was focused on the detailing of the connections (welded) especially since the proposed system is built on-site with limited quality control/assurance.

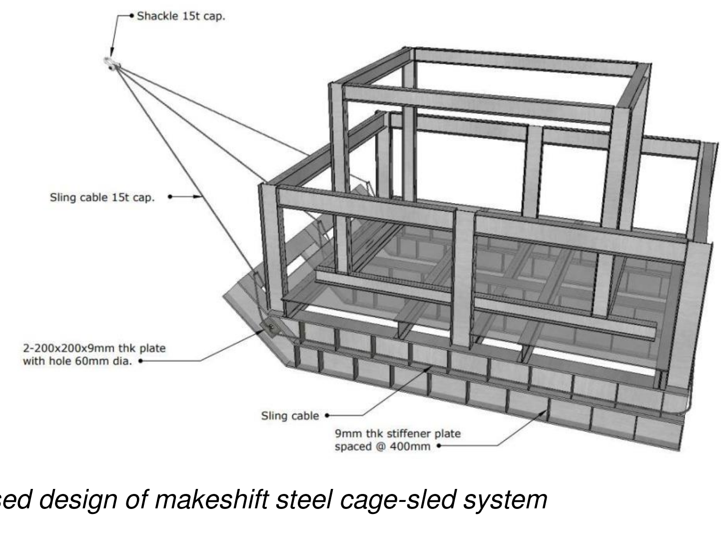

Figure 7. *Proposed design of makeshift steel cage-sled system*

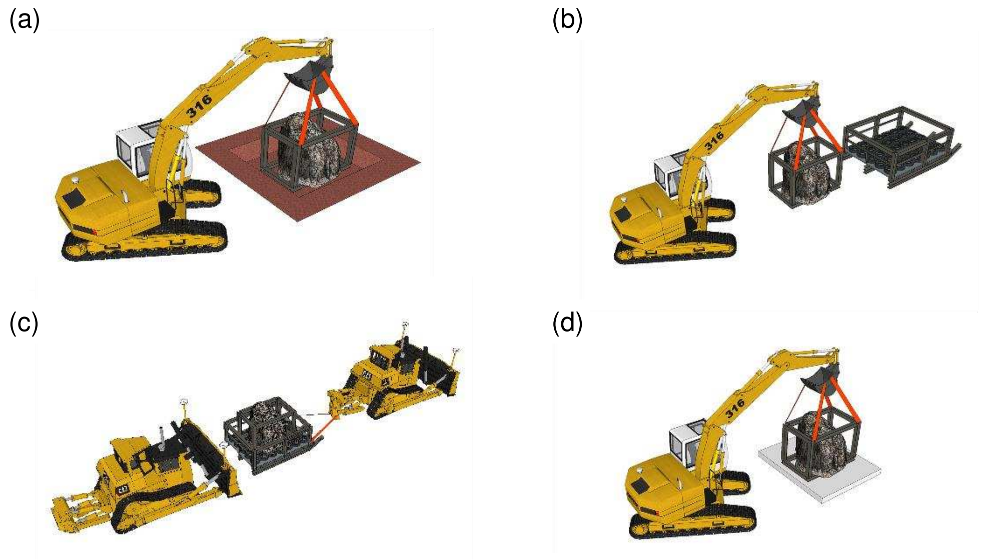

Figure 8. *Proposed relocation methodology: (a) welding and lifting the cage; (b) decking the cage onto the sled; (c) dragging the cage-sled system; and (d) unloading and disassembling the cage*

4.2 Actual transfer

After a series of review work and discussion with the Contractor, the proposed methodology and material specifications were approved as long as the actual transfer would not be continued while raining and that the lifting/unloading of the cage should be slow-paced as to not induce additional movement/swinging (and thereby stress on the slings and equipment). Moreover, additional provisions were required to wrap the Sacred Stone with geosynthetics to avoid direct contact between its surface and the steel members.

Ultimately, the Sacred Stone was safely relocated to Proposed Site 5, and the actual transfer was carried out within a span of two days (excluding earthworks for the access road) albeit a number of on-site adjustments and changes. The following figures show the photos taken during the actual transfer of the Sacred Stone.

Figure 9. *On-site photos during actual lifting (with blow-up images of connections)*

Figure 10. *On-site photos during transfer and after unloading*

5 CONCLUSIONS

Regardless of intention, any infrastructure project—especially major projects—should always consider the social and environmental implications that arise from its construction/development. This study is a prime example of properly looking at the overall impact of the project while proactively reaching out to those concerned and to those vulnerable to long-term post-construction hazards. Oftentimes, these considerations are overlooked up until the end of construction, or worse, only if something eventful happens. Due to the stakeholders' sense of responsible engineering, the local indigenous group are free to continue their religious practice without any worry of inundation or slope instability. Moreover, reviewing the Contractor's method statement and material specifications played a significant role in this endeavor because the on-site adjustments during the actual transfer may not have been done without adequate understanding of the situation and conditions of the Sacred Stone, the slopes, and the structural capacities of the equipment/systems used.

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