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Hydrological Effects on Rock Mass Quality and Rippability of Heterogeneous Karstic Limestone

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Abstract

The proposed study area is located approximately 1.9 km southwest of the main cement plant in Tuban, Indonesia. This research aims to evaluate the rippability characteristics of the limestone formation underlying the planned development site. The assessment is based on data obtained from a geotechnical borehole investigation (CR-1), integrated with previous subsurface exploration results. The site is designated for shallow foundation systems designed to withstand bearing pressures ranging from 300 to 800 kPa. Subsurface conditions are characterized by karstic limestone with complex hydrogeological features. The limestone exhibits high sensitivity to water infiltration, dissolution processes, and mechanical property degradation under saturated conditions. Significant spatial variability in rock mass quality and strength is observed over relatively short vertical and horizontal distances. The uppermost layer comprises residual lateritic (red) soil derived from in-situ weathering of the underlying limestone. The presence of limestone gravels and boulders within the residual soil indicates a transitional interface between the overburden and the more competent limestone strata. The limestone formation consists of heterogeneous materials, including highly porous honeycomb-textured rock and relatively intact, sound limestone, distributed irregularly across the site. This heterogeneity results in considerable variability in mechanical strength and excavation response. The findings provide essential insights into the rippability behavior of the limestone and its implications for foundation design and construction planning in karst environments.

Keywords: karstic limestone, rock rippability, rock mass variability, shallow foundation design, engineering geology

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INTRODUCTION

Karstic limestone formations constitute one of the most geotechnically challenging geological environments for infrastructure development. Their complexity arises from the combined effects of depositional heterogeneity, tectonic fracturing, chemical dissolution, and prolonged weathering processes. In tropical regions, where high rainfall and elevated temperatures accelerate chemical weathering, carbonate rocks undergo intense dissolution that generates irregular subsurface morphologies, including cavities, enlarged joints, conduits, sinkholes, and honeycomb-textured porosity. These features produce strong spatial variability in rock mass quality and mechanical behavior over short vertical and lateral distances. As a consequence, predicting excavation performance and foundation response in karst terrains remains a major engineering concern (Benischke, 2021).

Among the various engineering considerations in limestone terrains, rippability assessment is particularly critical during construction planning. Rippability refers to the capacity of rock to be excavated using mechanical ripping equipment without the need for drilling and blasting. The selection between ripping and blasting has significant economic, environmental, and safety implications (Doerfliger et al., 1999). Mechanical ripping is generally preferred in projects near industrial facilities or populated areas due to lower vibration, reduced environmental disturbance, and improved operational efficiency. However, its feasibility depends strongly on rock mass properties such as intact rock strength, degree of weathering, discontinuity spacing, fracture persistence, and overall mass integrity. In heterogeneous limestone, these parameters can vary abruptly, making excavation performance difficult to predict using conventional classification systems alone (Bailly-Comte & Pistre, 2021).

Hydrological conditions exert a fundamental control on the evolution and mechanical behavior of karstic limestone. Water acts not only as a mechanical agent influencing pore pressure and effective stress but also as a chemical driver of carbonate dissolution. The interaction between infiltrating groundwater and calcite-rich limestone enlarges discontinuities and enhances secondary porosity. Over time, dissolution processes reduce intact rock strength, weaken cementation bonds, and promote the formation of irregular voids. Seasonal or long-term fluctuations in groundwater levels may further accelerate deterioration by inducing cyclic wetting and drying, thereby altering the microstructure and fabric of the rock. Consequently, the mechanical response of limestone under saturated conditions may differ substantially from that under dry conditions (Assunção et al., 2023).

In addition to dissolution, hydrological processes influence weathering profiles and the development of residual soils overlying limestone formations. In tropical climates, prolonged exposure to rainfall and surface runoff leads to in-situ weathering of carbonate rock, forming residual lateritic soils rich in iron oxides and clay minerals. These soils often contain relict limestone fragments, gravels, and boulders that mark transitional interfaces between overburden and underlying competent strata (Berglund et al., 2019). Such interfaces are rarely planar or uniform; instead, they reflect progressive dissolution and irregular rockhead morphology. From an engineering perspective, these transitional zones present significant uncertainty because their mechanical properties differ from both the residual soil above and the more intact limestone below. This complexity directly influences bearing capacity, settlement behavior, and excavation resistance (Clark & Fritz, 2013).

Rock mass quality in karstic limestone is typically evaluated using classification systems such as Rock Quality Designation (RQD), Rock Mass Rating (RMR), or Geological Strength Index (GSI). While these systems provide useful frameworks for characterizing discontinuity conditions and overall rock mass integrity, they may not fully capture the influence of hydrological degradation mechanisms (Goldscheider et al., 2020). For example, a rock mass exhibiting moderate RQD values may still display low excavation resistance if dissolution features and saturation-induced weakening are significant. Similarly, intact rock strength measured under laboratory-dry conditions may overestimate field performance where groundwater infiltration is active. Therefore, a comprehensive assessment of limestone rippability requires integration of geotechnical parameters with hydrogeological context (Hillebrand et al., 2015).

Previous studies on limestone excavation performance have emphasized correlations between rippability and parameters such as unconfined compressive strength (UCS), seismic wave velocity, discontinuity spacing, and weathering grade. Empirical charts and equipment-based guidelines have been widely applied in practice (Hartmann et al., 2014). However, in highly heterogeneous karst environments, reliance solely on mechanical indices may lead to inaccurate predictions because localized dissolution zones, honeycomb porosity, or saturation effects can significantly reduce effective strength. Moreover, spatial variability in karst terrains often occurs at scales smaller than typical borehole spacing, introducing additional uncertainty in subsurface modeling (Filippini et al., 2018).

The need to better understand hydrological controls on rock mass behavior becomes even more critical when shallow foundation systems are planned. Shallow foundations designed to sustain moderate to high bearing pressures require reliable characterization of near-surface strata. In karstic limestone, load transfer mechanisms may be influenced by the presence of cavities, weakened zones, or irregular rockhead topography (Zou et al., 2023). Variations in moisture content and groundwater conditions can modify stiffness and strength, potentially affecting settlement performance and long-term stability. Hence, excavation planning and foundation design should not be treated as independent processes but rather as interconnected aspects governed by the same geological and hydrological framework (Toran & Reisch, 2013).

The study area considered in this research is located approximately 1.9 km southwest of a major cement plant in Tuban, Indonesia, within a region characterized by extensive limestone formations (**Figure 1**). The site is designated for infrastructure development supported by shallow foundation systems designed to withstand bearing pressures in the range of 300–800 kPa. Preliminary investigations indicate that the subsurface consists of karstic limestone exhibiting significant heterogeneity (Yang et al., 2010). The uppermost layer comprises residual lateritic soil derived from in-situ weathering of the underlying limestone. Limestone gravels and boulders embedded within this soil mark the transitional boundary between overburden and more competent rock. Beneath this layer, the limestone formation includes both highly porous honeycomb-textured rock and relatively intact, sound limestone, distributed irregularly across the site (Ravbar et al., 2023).

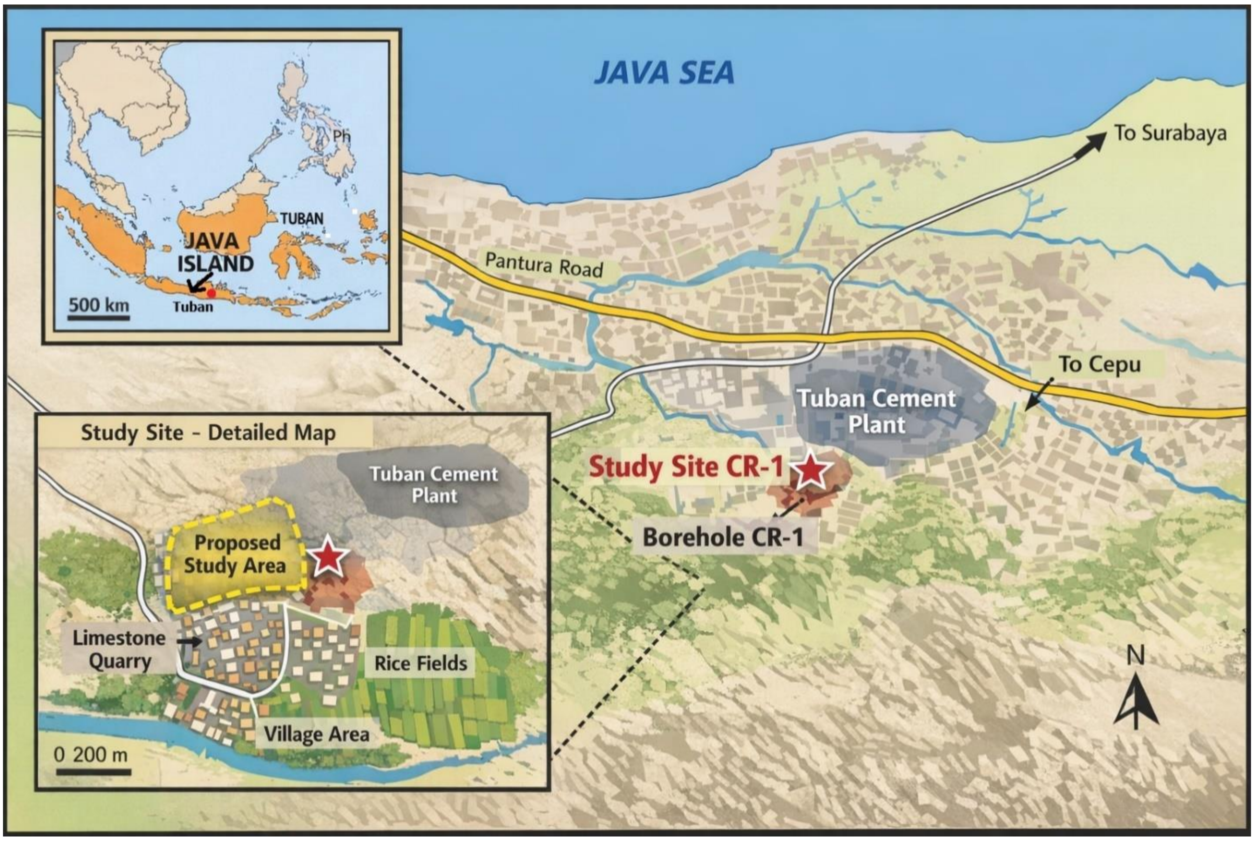

Figure 1. Study area location map

Field observations and borehole data reveal substantial variability in rock mass quality over relatively short distances. Such variability is interpreted to be closely associated with karst development and hydrological processes. The limestone exhibits sensitivity to water infiltration and dissolution, suggesting that mechanical properties may degrade under saturated conditions. These characteristics raise important questions regarding excavation strategy, equipment selection, and the reliability of shallow foundation performance (Pratama et al., 2021).

Despite the recognized importance of hydrological influences in karst terrains, limited research has explicitly examined the relationship between hydrogeological conditions, rock mass quality variability, and rippability behavior within a unified framework. Many engineering assessments treat hydrogeology primarily in terms of groundwater control or seepage management, without systematically linking it to mechanical degradation and excavation response. This gap highlights the need for integrated studies that combine geological, geotechnical, and hydrological perspectives to improve predictive capability in heterogeneous limestone environments (Mudarra & Andreo, 2011).

Accordingly, this study aims to evaluate the hydrological effects on rock mass quality and rippability of heterogeneous karstic limestone at the Tuban site. The assessment is based on detailed analysis of geotechnical borehole data integrated with prior subsurface investigations. By examining weathering profiles, lithological variability, and hydrogeological characteristics, the research seeks to clarify how water-related processes influence mechanical behavior and excavation feasibility (Field, 2002). The findings are expected to contribute to improved excavation planning, risk mitigation, and foundation design strategies in karst environments, while also advancing understanding of the coupling between hydrological processes and rock mass engineering properties (**Figure 2**). Through this integrated approach, the study positions hydrology not merely as a background environmental factor but as a central mechanism governing rock mass heterogeneity and rippability performance in karstic limestone (Fang, 2019).

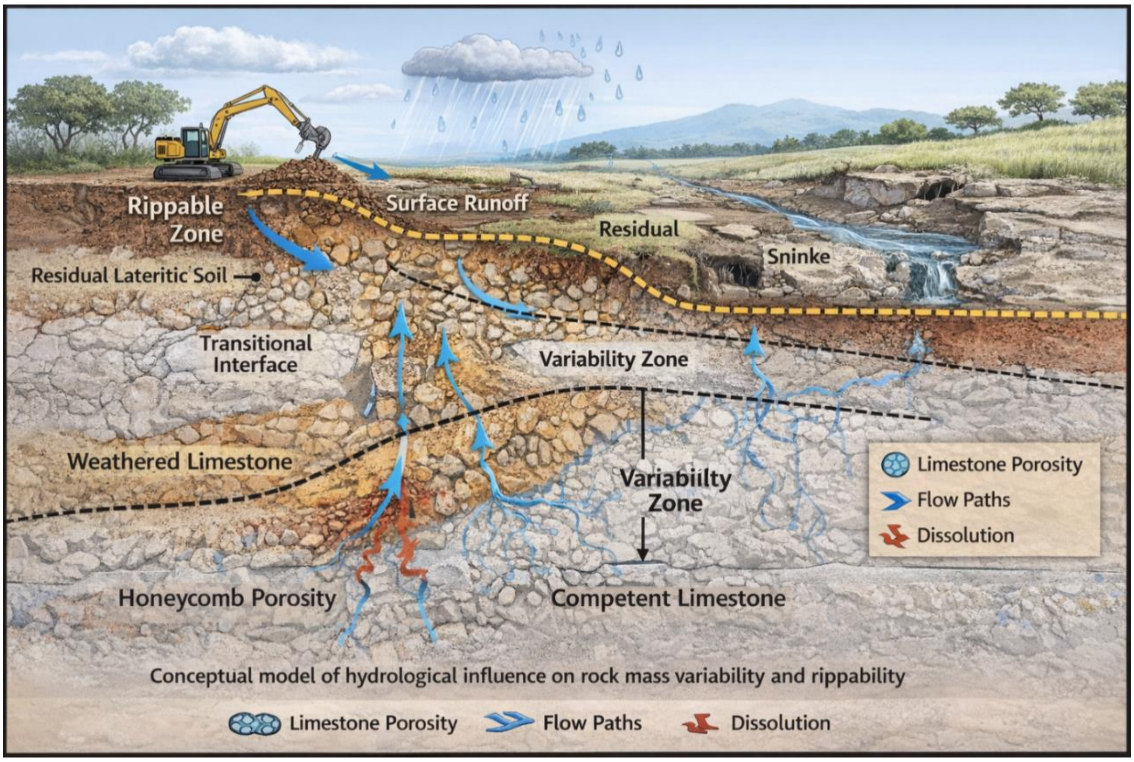

Figure 2. Conceptual model of hydrological influence on rock mass variability and rippability

METHOD

Subsurface Investigation and Sampling

The evaluation of limestone rippability at the proposed development site was based on data obtained from a geotechnical borehole investigation (CR-1). The borehole was drilled to a depth of 20 m below ground surface. The subsurface profile consists of approximately 1 m of reddish-brown clayey residual soil containing limestone gravels and boulders, underlain by limestone bedrock extending to the bottom of the borehole. The residual soil represents in-situ weathering of the underlying carbonate formation and marks the transitional interface between overburden and competent rock. Below this layer, the limestone exhibits variable degrees of weathering and heterogeneity, consistent with karstic development. Four intact rock core samples were selected from depths between 2 m and 14 m for laboratory strength testing. The selected intervals were chosen to represent the variability observed in lithology and weathering grade along the borehole.

Laboratory Testing

To characterize the mechanical properties controlling excavation resistance, two primary strength parameters were determined:

- Unconfined Compressive Strength (UCS)
- Point Load Strength Index (PLI or Is(50))

UCS tests were conducted on prepared cylindrical specimens in accordance with standard rock testing procedures (e.g., ISRM suggested methods). The measured UCS values range from approximately 4.5 MPa to 14 MPa. This range indicates weak to moderately strong limestone according to common rock strength classifications. Point load tests were performed to obtain the point load strength index, which provides a rapid and practical estimation of intact rock strength. The measured Is(50) values range from approximately 0.5 MPa to 2.7 MPa (equivalent converted UCS values approximately 5–27 MPa depending on correlation factors). The significant variation in both UCS and point load index reflects the heterogeneity of the limestone, likely associated with differential weathering, dissolution features, and variability in porosity. The wide strength range observed over relatively short vertical intervals confirms that the rock mass quality at the site is spatially variable, a characteristic typical of karstic limestone environments (Adams et al., 2001).

Seismic Velocity Measurement

Seismic velocity data were used as an indirect indicator of rock mass quality and rippability. Longitudinal (compressional or P-wave) seismic velocity measurements provide an integrated representation of intact rock properties, discontinuity conditions, porosity, and degree of weathering. To estimate the rippability of the rocks found at borehole CR-1 we used the charts shown in **Figures 3** to **Figure 5** below. Lower seismic velocities generally correspond to highly fractured, weathered, or porous limestone, which is more favorable for mechanical ripping. Conversely, higher velocities indicate more competent and intact rock masses that may require blasting or heavy-duty ripping equipment.

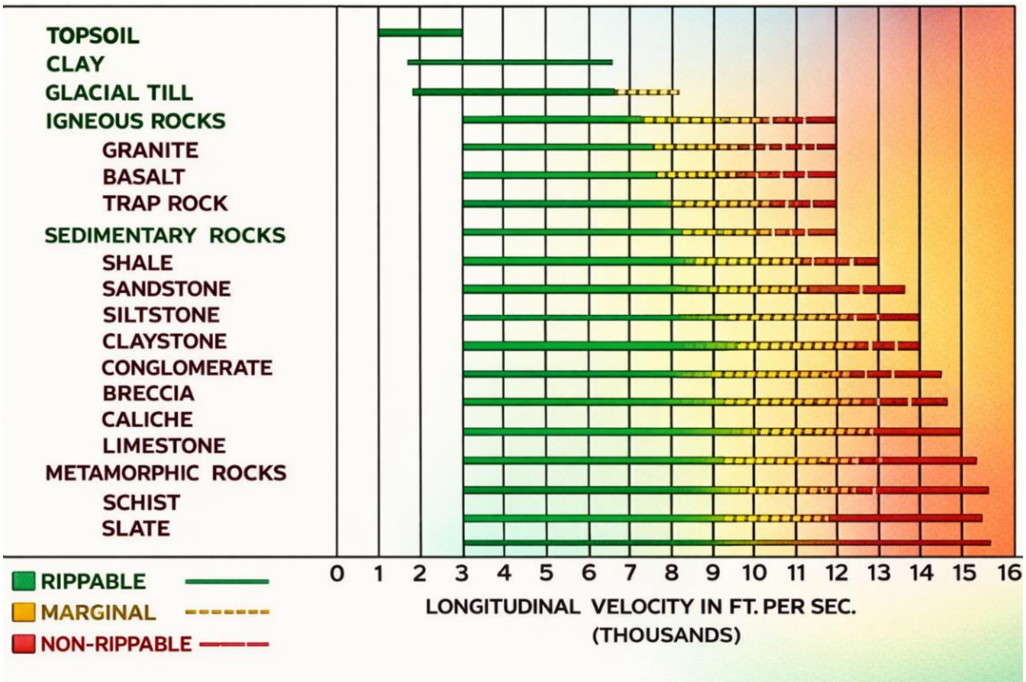

Figure 3. Rippability of Subsurface Materials Related to Longitudinal Seismic Velocity (in thousands of ft per second) for a Heavy Duty Ripper (Tractor-Mounted) (NAVFAC DM 7.02)

Rippability was evaluated using empirical correlations between seismic P-wave velocity and excavation performance. The assessment was based on established rippability charts published in:

- NAVFAC DM 7.02 (Foundations and Earth Structures)
- Caterpillar Performance Handbook (2006)

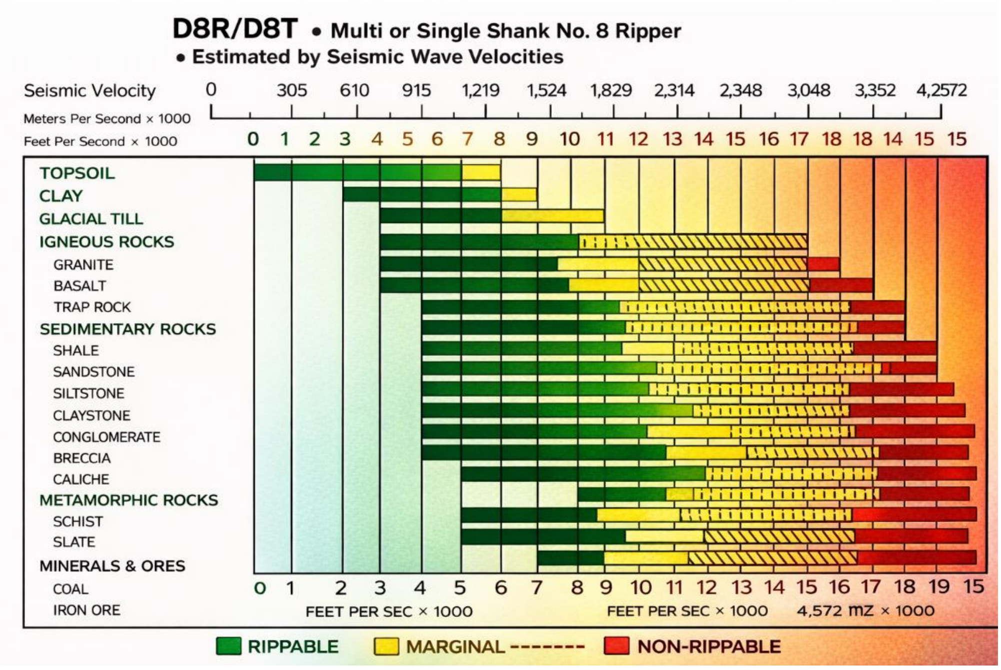

Figure 3. Caterpillar D8R/D8T Ripper Performance Estimated by Compression (Longitudinal) Seismic Velocity

These charts classify soil and rock materials into rippable, marginally rippable, or non-rippable categories based on longitudinal seismic velocity ranges and equipment capability. The seismic velocity values obtained at borehole CR-1 were plotted against the empirical charts to determine the expected excavation method suitability. The classification provides an estimate of whether the limestone can be excavated using conventional ripping equipment (e.g., hydraulic ripper or jackhammer attached to backhoe excavator) or whether blasting would be required (Barberá & Andreo, 2015). In addition, laboratory-derived strength parameters (UCS and point load index) were used to support and cross-validate the seismic-based rippability interpretation. The combined use of direct strength measurements and geophysical indicators improves reliability, particularly in heterogeneous rock masses.

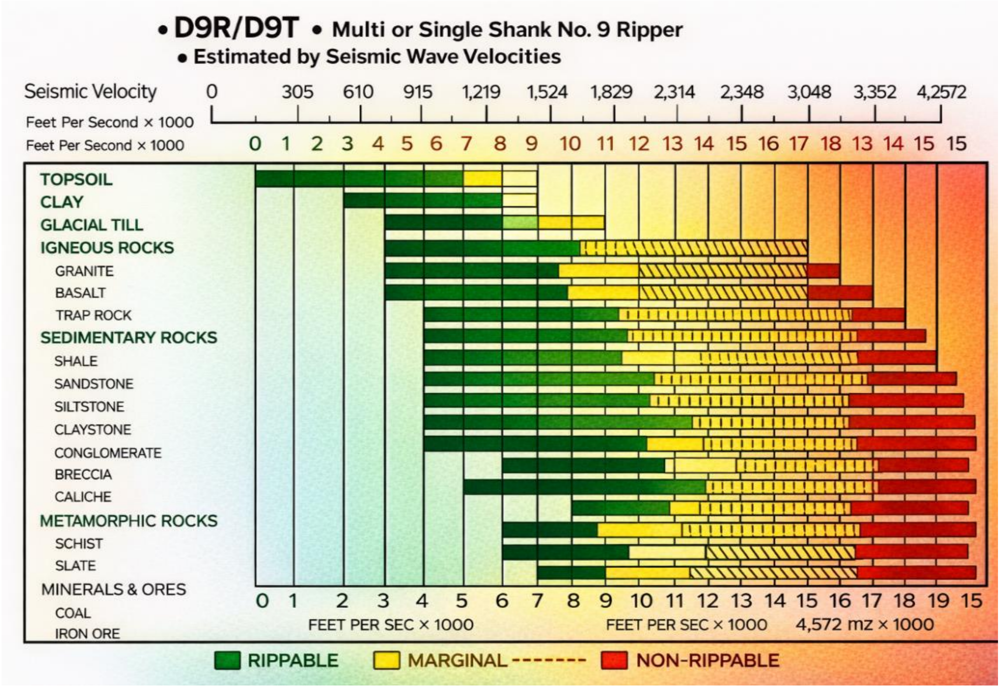

Figure 5. Caterpillar D9R/D9T Ripper Performance Estimated by Compression (Longitudinal) Seismic Velocity

Consideration of Operational Factors

Although empirical rippability charts provide useful guidance, excavation performance is also influenced by operational and equipment-related factors. These include:

- Ripper tooth penetration capability
- Tooth geometry and orientation
- Machine weight and horsepower
- Operator skill and experience
- Presence of localized dissolution cavities or hard rock lenses

Therefore, the rippability classification derived from seismic velocity and strength data should be interpreted as an engineering estimate rather than an absolute determination. Field verification during excavation remains essential, particularly in karstic terrains where localized variability may significantly affect performance (White et al., 2018).

Integration with Previous Excavation Experience

Previous excavation works at the main cement plant site indicate that similar limestone formations were successfully excavated using a hydraulic jackhammer attached to a backhoe excavator. This practical experience provides additional support for interpreting the limestone at borehole CR-1 as mechanically excavatable under certain strength and weathering conditions (Ji et al., 2022).

RESULTS AND DISCUSSION

Shear Wave Velocity Test

To apply the above charts, the shear wave velocity (Vs) of the rock mass was estimated through correlation analysis between the geological characteristics observed in borehole CR-1 and the laboratory and field test results obtained from our previous study (Geotechnical Investigation for the Tuban Cement Plant Project). As shown in **Figure 6**, shear wave velocity measurements were carried out at eight locations across the main plant area, extending to a depth of approximately 30 m below ground surface.

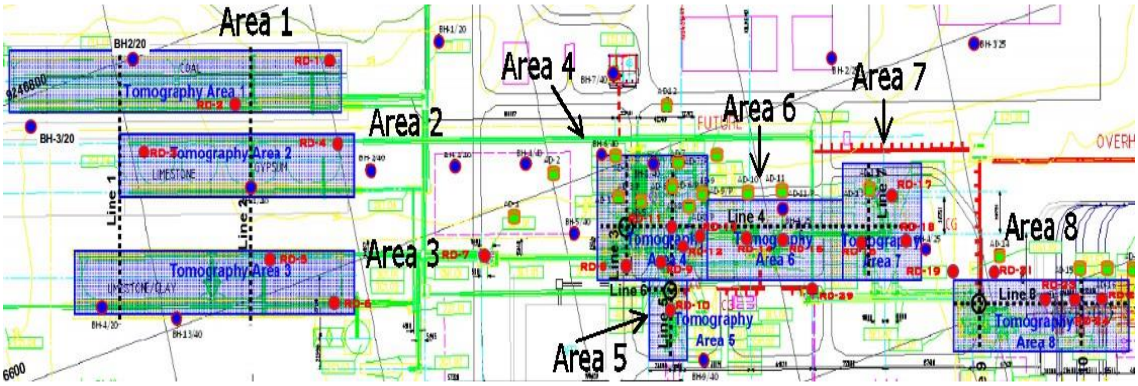

Figure 6. Shear Wave Velocity Test Sites at the Main Plant Area

The **Figure 6** illustrates the layout of geophysical testing and geotechnical investigations at the main plant site, which is divided into eight observation zones (Area 1 to Area 8). Each area represents locations where seismic tomography surveys were conducted, along with boreholes (BH) and additional test pits/supplementary drillings (RD) used for subsurface data correlation. In general, the division of these areas aims to:

1. Identify lateral variations in soil and rock conditions.
2. Estimate the distribution of shear wave velocity (Vs) values to a depth of approximately ±30 m.
3. Correlate geophysical test results with borehole data (CR-1 and other boreholes).

4. Determine ripability classification based on the relationship between seismic wave velocity and material type.

Areas 1–3 are located in the western part of the site and are dominated by limestone zones based on previous investigation results. Tomographic surveys in these areas were focused on evaluating the degree of weathering of carbonate rocks and variations in overburden thickness (Maréchal & Etcheverry, 2003). Areas 4–6 are situated in the central part of the site and show the highest density of investigation points. This indicates that these zones correspond to the main structural areas of the plant buildings, requiring more detailed investigations to reduce uncertainty in subsurface conditions (Vadillo & Ojeda, 2022). The high data density in these areas allows for a more representative and accurate interpretation of the Vs model. Areas 7–8 are located in the eastern part of the site and exhibit more complex geological variations based on the distribution of RD and BH points. Investigations in these areas are important to identify possible changes in lithology or rock mass compactness that may influence excavation methods. From the distribution of investigation points, it can be seen that the investigation approach was carried out systematically using a combination of:

1. Boreholes (BH) to obtain direct stratigraphic data,
2. RD points as additional control points,
3. Seismic tomography to obtain a continuous shear wave velocity model.

The integration of these three methods enhances the reliability of shear wave velocity (Vs) estimation, which is subsequently used to determine rippable, marginal, and non-rippable classifications in accordance with the previously presented ripability chart. Thus, the figure demonstrates that the investigation was conducted comprehensively and evenly distributed across critical construction areas, enabling a more accurate interpretation of subsurface conditions to support excavation planning and heavy equipment productivity estimation (Parkhurst & Appelo, 2013).

Point Load Index Strength

In **Figure 7** the plotted point load test index from the site and from Area 1, 2, and 3 of the main plant site indicate similarity of the rock conditions among these sites.

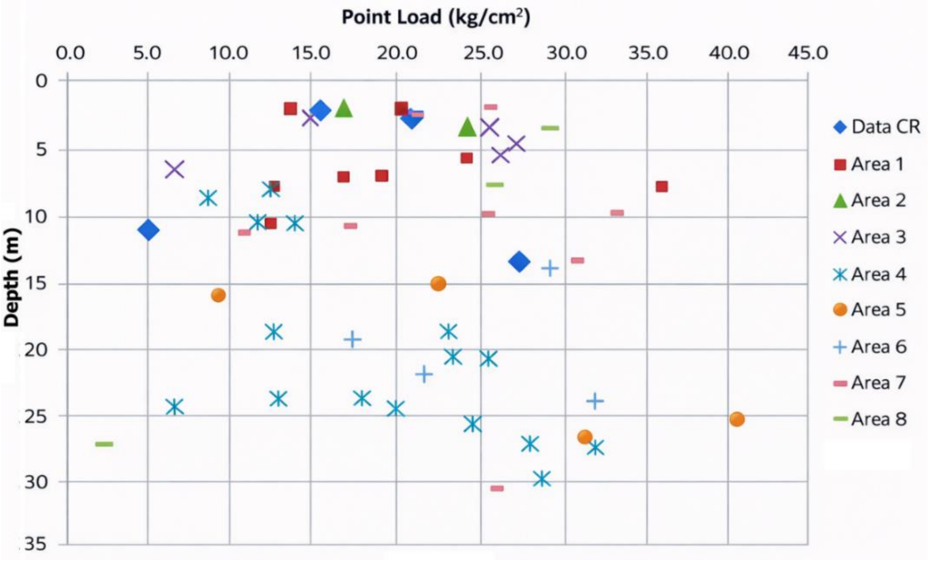

Figure 7. Point Load Index Strength Variation

The point load test results reveal significant variability in rock strength with depth (**Figure 7**). Measured values range from approximately 5 to 45 kg/cm², indicating a wide spectrum of mechanical competence within the investigated limestone formation. Importantly, no systematic increase in strength with depth is observed. Instead, abrupt fluctuations occur over relatively short vertical intervals. Such behavior is atypical for homogeneous sedimentary rock sequences but is characteristic of karstified carbonate formations (López-Chicano et al., 2001). In these settings, rock mass quality is controlled primarily by dissolution intensity, fracture connectivity, and secondary porosity development rather than burial depth alone. The absence of a consistent strength gradient suggests that mechanical stratification is disrupted by karst processes. In the uppermost interval, point load values generally range between 10 and 30 kg/cm^2, with occasional lower values. This zone corresponds to the transitional interface between residual lateritic soil and the underlying limestone bedrock. The presence of limestone gravels and boulders within the residual soil indicates in-situ weathering and progressive degradation of the parent rock (Eftimi & Malík, 2019). The moderate to low strength values in this interval are likely associated with:

- Partial weathering,
- Micro-karstification,
- Increased porosity due to dissolution,
- Possible seasonal water infiltration.

From a rippability perspective, materials in this depth range are generally classified as rippable to moderately rippable using heavy-duty bulldozers. However, localized harder blocks may create operational variability during excavation. Between 10 and 20 m depth, the data show pronounced heterogeneity (Cattell, 1966). Strength values fluctuate between approximately 12 and 30 kg/cm^2 within short vertical distances, including within the same borehole (CR-1). This variability indicates:

- Irregular distribution of intact limestone blocks,
- Alternation between honeycomb-textured porous rock and relatively sound limestone,
- Differential dissolution intensity influenced by groundwater pathways.

Hydrogeological influence becomes increasingly significant in this interval. Under saturated conditions, carbonate dissolution and microfracture weakening reduce the effective strength of the rock mass. The mechanical response is therefore strongly dependent on both lithological heterogeneity and hydrological state. In terms of rippability:

- Values below 20 kg/cm^2 are generally rippable,
- 20–30 kg/cm^2 represent marginal ripping conditions,
- Localized harder zones may require auxiliary mechanical breaking.

Intact Rock Compressive Strength

The unconfined compressive strength (UCS) plotted from the site and from Areas 1, 2, and 3 of the main plant site in **Figure 8** shows that the rock conditions at these locations are similar

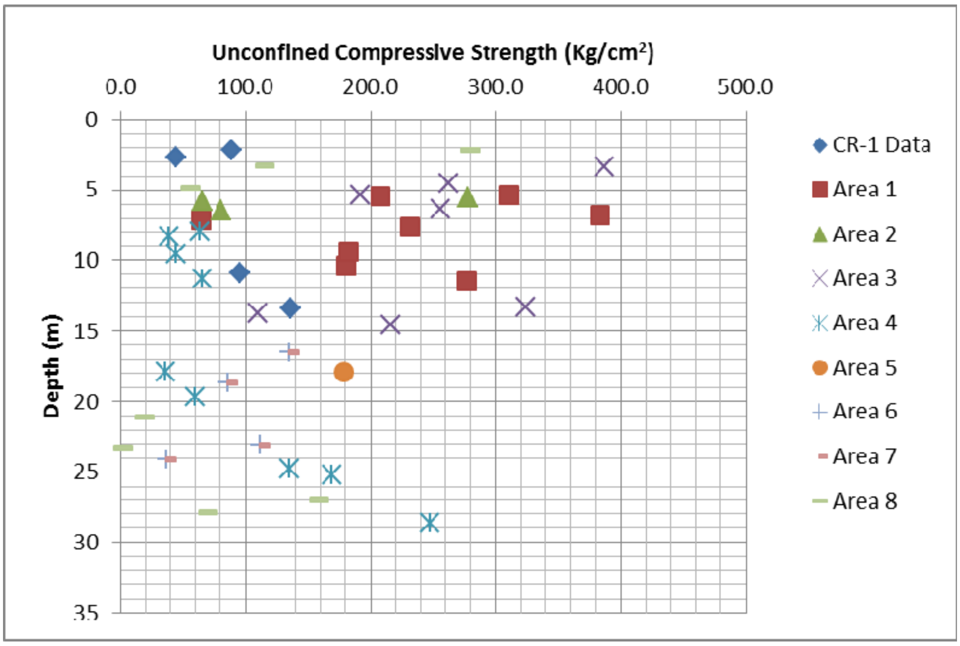

Figure 8. Intact Rock Compressive Strength Variation with Depth

The Unconfined Compressive Strength (UCS) results exhibit a wide strength range, approximately between 50 and 450 kg/cm^2 (**Figure 8**). Similar to the point load results, no consistent increase in UCS with depth is observed. Instead, the data demonstrate strong vertical and lateral variability across the investigated areas (Lastennet & Mudry, 1997). The absence of a progressive strength increase with depth suggests that lithological continuity is disrupted by karstification processes. In intact sedimentary sequences, UCS typically increases due to reduced weathering and compaction effects at greater depths (Ji et al., 2022). However, in this karstic limestone formation, dissolution-driven heterogeneity appears to override depth-dependent strengthening (Lauber & Goldscheider, 2014).

Shear Wave Velocity

In **Figure 9** the plotted the shear wave velocity test from the site and from Area 1, 2, and 3

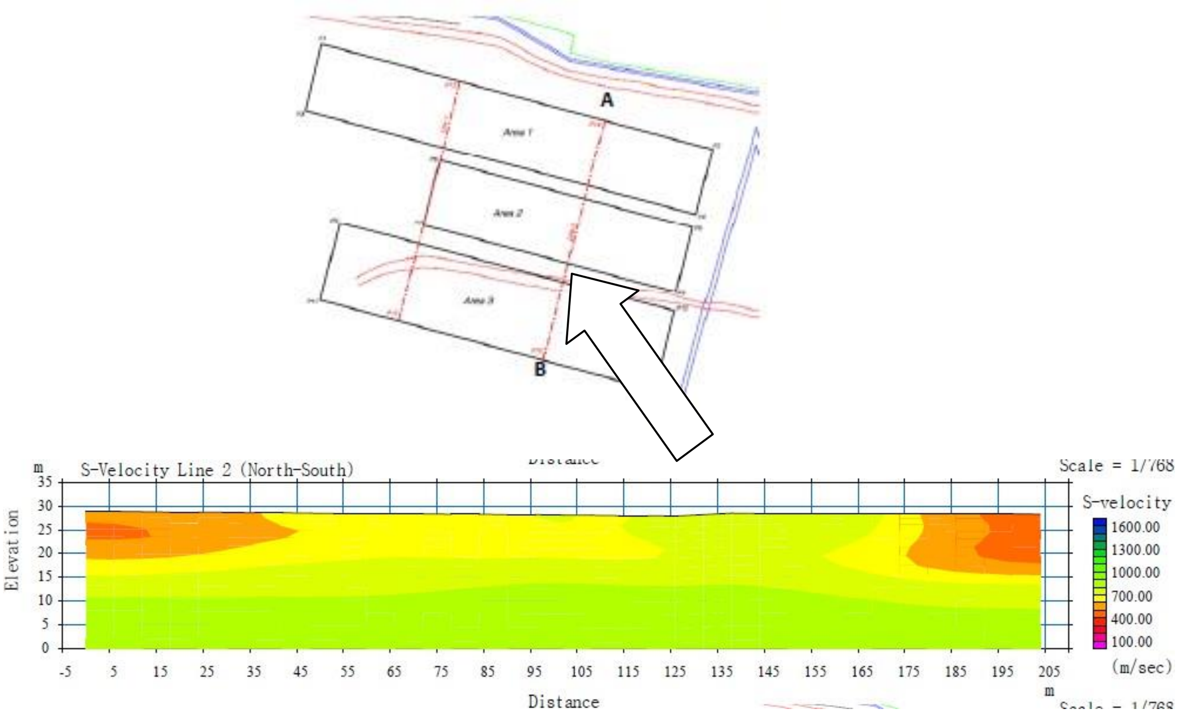

Figure 9. Shear Wave Velocity Across at Line 2 in Area 1, 2 and 3

The influence of hydrological conditions on rock rippability includes:

a. Water entering through fractures, joints and bedding planes will increase the degree of saturation, fracture enlargement and weathering.
b. Water-saturated limestone experiences a decrease in: compressive strength, cohesion, elastic modulus, effective stress and shear strength.
c. The impact is that rock rippability is easier but slope stability decreases.

CONCLUSION

This study successfully evaluated the excavability of heterogeneous karstic limestone using three complementary approaches: the Point Load Index (PLI), Unconfined Compressive Strength (UCS), and seismic wave velocity measurements. The integration of these methods provided a consistent assessment of rock mass behavior and excavation response across the investigated areas. The results derived from PLI and UCS testing indicate considerable variability in intact rock strength, while seismic velocity data further confirmed the heterogeneous nature of the limestone mass. At the test sites in Areas 1, 2, and 3, the measured shear wave velocity (Vs) ranges from approximately 500 to 1000 m/s. The corresponding compressional (Vp) wave velocity varies between approximately 1000 and 2000 m/s, which is roughly twice the measured shear wave velocity, consistent with typical elastic wave relationships in fractured limestone. Based on established rippability charts correlating seismic velocity and rock strength, the limestone encountered at borehole CR-1 within the cement plant site can be classified as rippable using heavy-duty equipment comparable to Caterpillar D9R/D9T class bulldozers. However, the excavation response is not uniform. Significant vertical and lateral variability in mechanical properties reflects the strong influence of karstification and hydrogeological processes. Water infiltration, dissolution, and progressive weathering reduce intact rock strength and increase secondary porosity, thereby enhancing excavability. At the same time, these hydrological effects introduce mechanical discontinuities and heterogeneity within the rock mass. While increased saturation and dissolution improve ripping efficiency, they also pose engineering challenges, including reduced slope stability, differential stiffness distribution, and localized weak zones. Therefore, excavation and foundation planning in the Tuban limestone formation must account for hydro-mechanically controlled variability rather than assuming homogeneous rock conditions. Overall, the combined geomechanical and geophysical assessment provides a reliable framework for predicting rippability in complex karst environments.

AUTHOR CONTRIBUTIONS

Conceptualization, AEW; methodology, AEW, YM, and KY; software, BDR; validation, AEW, YM, and PM; formal analysis, AEW and KY; investigation, PM and RP; resources, YM; data curation, BDR and RP; writing—original draft preparation, AEW; writing—review and editing, AEW, YM, and KY; visualization, BDR; supervision, YM; project administration, AEW; funding acquisition, YM.

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CONFLICTS OF INTEREST

The authors declare no conflict of interest concerning the publication of this article. The authors also confirm that the data and the article are free of plagiarism.

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