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An innovative approach: Combining OTV logging and manual core logging for geotechnical site investigation – A case study from the Lesser Himalaya of Eastern Nepal

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ABSTRACT

Geotechnical exploration in the youngest Himalayan range requires a thorough understanding of subsurface geological conditions, including lithological, structural, and mechanical properties. Accurate data obtained from test boring, in-situ borehole tests, and logging are essential for this purpose. Down-hole optical imaging, such as the optical televiewer (OTV), can provide a cost-effective and efficient approach to capturing structural geotechnical data by providing high-resolution, oriented images of borehole walls. This study aims to test the effectiveness of a hybrid logging method that combines OTV imaging with manual core logging for geotechnical investigations in the eastern part of the Lesser Himalaya, Nepal. The hybrid method addresses inherent problems such as actual depth matching, errors in the reorientation of acquired cores, and ambiguity in the placement of weak zones like intensely fractured zones, fault gouges, and sheared zones. This approach is critical for identifying weak zones and ensuring safe and stable construction.

Keywords: Optical televiewer, hybrid logging, borehole logging, geotechnical investigation

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INTRODUCTION

The geology of the Himalaya is intricate and intriguing as it features numerous tectonic bodies and structures with adverse lithostratigraphic conditions (Shahi et al., 2022). These youngest mountains with the fragile geological condition and active tectonic settings contain deformed and weak rock mass at places; due to which the region is constantly plagued by stability issues (KC et al., 2022a,b; Dangi et al., 2019). Being located at the central part of the fragile and active Himalayan range, the Nepal Himalaya has fragile geology, ongoing tectonic activities, and complex geological structures are no exception. This point out the necessity of adequate and in-depth knowledge of subsurface conditions for engineering geological practices, during the early design phase of construction projects; which provides relative freedom available during construction planning. Detailed construction design requires detailed geotechnical exploration by drilling boreholes, hydraulic tests of boreholes, and examination of cores which gives the lithological, structural, and rock mechanical information of the subsurface. But the geotechnical log obtained from core drilling is sometimes ambiguous in terms of structural interpretation and representing real field conditions when core recovery is very low. Also, it is more time-consuming as it is associated with manual core logging. To cope with a more extreme working environment, the development of more representative and reliability-based methods for down-hole characterization is needed (Kao et al., 2020). Down-hole image logging by acoustic televiewer (ATV) and optical televiewer (OTV) could be best suited as they are deployed in the borehole and can display the occurrences of breakouts, fractured zones, and weak planes. This facilitates many applications in geotechnical site investigation, ranging from the evaluation of rock mass porosity, the identification of induced fractures, the measurement of strike and dip in the borehole, and the use in the construction of a fracture network model (Thill and D'Andrea, 1976; Tezuka and Niitsuma, 2000).

Although many researchers have attempted to incorporate down-hole imaging with geotechnical investigations, most of those only gave a semi-qualitative assessment of the integrity of geological formations (Gwynn et al., 2013). The ATV and OTV data were only taken for visualizing borehole structural features and played a minor role in complementing field mapping or conventional core logging. Based on our observations in practice, the down-hole imaging logs have been considered less important than other types of borehole logging techniques. For example, in hydrogeological studies, these logs were mainly applied for visualizing depth to groundwater table but lacked discussion on its potential for site characterization and hydraulic parameter estimation (Kao et al., 2020). Although considered less important, the use of ATV concerning the quantitative characterization in a field scale is more common than OTV for geotechnical site investigation. Many researchers (Kao et al., 2020; Schepers et al., 2001; Pollok et al., 2018) have explained the significance of ATV in the geotechnical investigation; while very few (Wedge et al.,

2017) have compared the performance of ATV and OTV only in terms of structural interpretation. The study incorporating a comparison of the OTV logs with continuous drilled core logs on the geotechnical investigation on a field scale is lacking; while not a single one exists within the Nepal Himalaya.

With an aim to demonstrate the importance of the conventional OTV logging technique for the geotechnical site investigation, the current study takes an exploratory borehole drilled at the Arun River catchment of the Sankhuwasabha District, within the Arun window as an example. It covers the fieldwork methodology for combining OTV data with core logging techniques. This hybrid logging method allows for the detailed description of physical behavior and structural features including open or healed discontinuities but also lithological contacts or foliations whilst making use of the accurate depth and structural orientation measurements obtained from the OTV data. The result provides a new way of thinking about the use of hybrid logging in geotechnical site investigation, as both qualitative and quantitative subsurface information can be obtained. Application of this technique could provide a more efficient assessment means for geotechnical investigations than current other methods.

DESCRIPTION OF THE STUDY AREA

The exploratory borehole is situated at an elevation of approximately 1800 m within one of the tectonic windows of the Nepal Himalayas, namely the Arun Window (Dhital, 2015). It consists of the Lesser Himalayan rock sequence surrounded by the higher Himalayan thrust sheet (Schelling, 1992), from a regional geological perspective. The topography of the area is rugged and uneven due to the presence of rocks with varying degrees of metamorphic grade and competency from south to north as Migmatites; Mica Schists with garnet, tourmaline, and infrequently staurolite and kyanite; Lower Quartzites containing biotite, garnet, and quartzite; Lower Phyllites; Upper Quartzites with chlorites, Calc-Schists and Upper Phyllites (Bordet, 1961).

METHODOLOGY

Several studies have incorporated geotechnical investigations for various purposes such as for assessing the suitability of rock mass for mining dimension stones (Mustafa et al., 2015), stability analysis of tailing dam (Wei et al., 2016), and slope stability analysis (KC et al., 2023). In all of these studies, geotechnical exploration revolves around a variety of methods, including drilling boreholes, examining cores, conducting laboratory measurements on cores, and performing mechanical and hydraulic tests in boreholes. For the present study, in order to undertake the hybrid approach of core logging, a systematic approach was taken for borehole drilling, rock core recording, and both manual and OTV logging. This study describes the orderly manner in which these techniques were carried out in the study area to facilitate geotechnical assessments as follows.

Drilling and manual core logging

To conduct the OTV survey, a stable borehole was drilled using core drilling equipment. Initially, the rotary core drilling method was used to obtain the samples, which were systematically placed in a core box with depth markings (Fig. 1). During drilling, geological logs were maintained by observing the core samples for better correlation with the optical images and to improve the understanding of the subsurface geological conditions. Clean water was flushed into the borehole to enhance the visibility of the geological discontinuities during the capture of down-hole images.

Core imaging (OTV)

Optical televiewers (OTVs) are increasingly used to capture structural geotechnical data for use in underground and pit slope design. They provide high-resolution, oriented images of borehole walls and can be used as a replacement for manual core orientation techniques, as in exploratory drilling, coring is typically non-oriented, meaning additional measurements are needed to reconstruct the initial spatial orientation and thickness of drilled cores. In this study, a borehole TV system was used to produce optical images of the full circumference of the drilling core in 24-bit RGB true color, with a resolution of 360–1440 pixels. The system includes a high-resolution probe (2 m length, 8 mm diameter), micro blogger, winch with cable, laptop, depth encoder, interface communication tool, tripod, non-magnetic centralizers, batteries or power supply, and multicore cables with multipin connectors. The system has a four-core cable mounted in an automatic winch with a downhole length capacity of 500 m.

During imaging, the cores are rotated about their longitudinal axis and are scanned by a digital line-scanning camera. The rotation of the drilling core is registered using an incremental

Fig. 1: Core logs obtained from rotary drilling (45–50 m).

rotary position transducer, and a new line is scanned every time the circumference rotates by an increment of a pixel. The scanning software (OPTV logger) processes the scanned data and generates a true-color core image. The system provides unrolled circumferential imaging of cores (Fig. 2a), surface imaging of slabbed cores (Fig. 2b), structural and statistical analysis, core image analysis, and documentation of drilling cores.

Acquisition and processing of televiewer data

To capture the down-hole image, the optical probe was attached to the logging cable with two non-magnetic centralizers. The probe was inserted into the borehole, suspended on a tripod-supported depth-encoding wheel. Once all the connections were made, the logging software was used to turn on the probe. The probe depth was set up to the logging datum, and a new file was created for recording. The probe was then lowered at a rate of 2.0 m/min, and the OPTV logger's user interface window displayed the probe's depth and speed on the computer screen. The left panel also showed the tool temperature, cable tension, and orientation information. The right panel displayed the record control, power supply tool, communication status, setup tool, illumination controls, image compression, vertical resolution, and natural gamma status. Once the probe reached the bottom of the hole, the winch was stopped, and the project was exported in the header file (.hed) and data file (.OTV) format. After completing the downward logging, upward logging was initiated by setting up the new project's bottom level. The logging data could be reviewed on the screen and then saved on the computer screen. Power was cut off after the probe was removed from the borehole.

The GeoCAD software was utilized for processing, interpreting, and displaying OTV logs with a tadpole and stick plots, stereographic projections of poles to planes, and azimuth frequency diagrams. The obtained OTV logs were unrolled and displayed from 0 to 360 degrees, oriented to magnetic north. Structural features like foliation planes and fractures intersecting the borehole appeared as sinusoids, either full or partial (Fig. 3), whose extreme values were related to the spatial orientation of structures. The sinusoidal projections of the structures were chosen from the images. The projections of foliations and fractures were represented by several sinusoidal legends, whose spatial orientations were calculated using the approach introduced by Pollok et al. (2018). The resulting dips could be further displayed as a rose diagram, histogram, or stereo plot using various software like Dips (RocScience) and Excel.

Data validation/calibration using drill core

The GeoCAD software was used to import, present, and compare the original core log and core photo (Fig. 2). During drilling, the physical core was logged using an Excel spreadsheet program. This process involved noting the type of rock, fracture frequency, rock quality designation (RQD), total core recovery (TCR), weathering, mineral composition of rocks, structures, and alteration present on the core. This manual operation presented the solid core characteristics along with the core photographs. Fractured zones and core loss zones

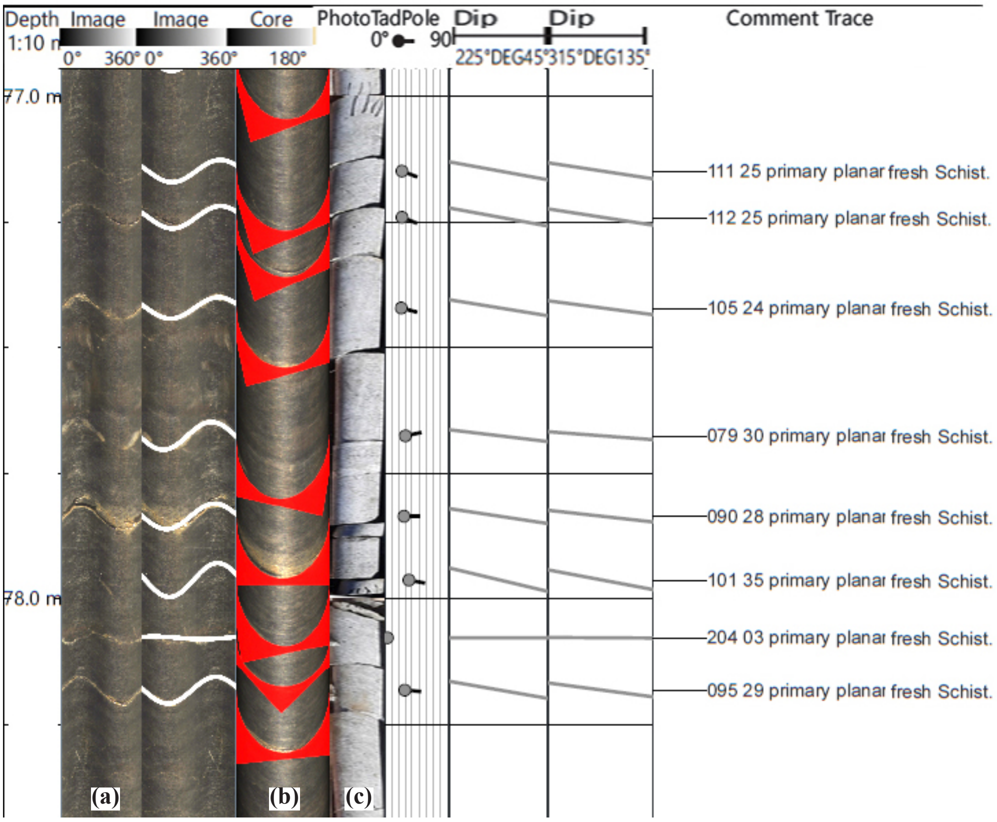


Fig. 2: Down-hole optical logging results compared with manual core logging (a) unrolled circumferential imaging of cores (white color shows discontinuity markings), (b) surface imaging of slabbed cores (red planes demarcates visible discontinuity planes), and, (c) manual core log obtained from rotary drilling.

were marked in the log and core box. The optical televiewer survey was then used to confirm any missing information.

RESULTS

The lithological and structural interpretations, along with their orientations, obtained from the borehole televiewer image analysis and manual core logging, are discussed in the following sections.

Test boring

The characterization of rock mass quality is one of the most necessary information required during the pre-construction phase of geological investigation to evaluate the economic viability of projects during planning (Panthi and Nilsen, 2006). And one of the most reliable and direct methods of assessing information about rock mass quality tests is boring. So, a test borehole of NQ size (47.6 mm coring size) was drilled to a depth of 80 m, and the drill cuttings were analyzed for preliminary identification of rock types and discontinuities. The manual logging of the borehole represents a monotonous lithology of the schist with different discontinuity settings and weathering conditions. They reported a groundwater table at a depth of 60 m. The rock quality designation index of the test core (RQD), which is the percentage of intact core pieces longer than 100 mm, range from 14 to 95% (Fig. 4), with an average of 50.27%.

From the illustration, it is clear that the distribution of rock quality in the borehole shows a gradual positive increase with depth. In this area, the majority of rock quality ranges from poor (RQD = 25–50%) to fair (50–75%), while the value for intensely fractured zones is very poor (0–25%).

Lithological and alteration features

General mechanical and hydraulic properties of the exploration area can be predicted if the lithologies that will be encountered are already identified. Lithological descriptions can provide specific properties for each lithology. For example, lithological information could indicate changes in mechanical properties in the presence of water. In this case, lithological information was obtained by inspecting outcrops, examining cores, and processing borehole images. The borehole was continuously cored and a detailed analysis of the core was carried out. Later on, detailed lithological information was obtained from OTV logs, as core recovery at certain depths was poor and OTV images helped detect thin layers of weak material that are often washed out of core sections. Due to the presence of uniform lithology, i.e., schist, no visible color contrast was observed in the OTV logs to identify mineral composition and filling. From outcrop inspection and information from both logs, it is evident that uniform lithology of weakly foliated, moderately to unweathered, light to dark grey schist is present throughout the borehole, and alteration is not so evident.

Structural interpretation

The high-resolution optical televiewer image under analysis reveals several remarkable drilling characteristics. The optical televiewer image was used to evaluate the geometry of borehole discontinuities such as foliations, segment fractures, hairline fractures, en-echelon fractures, and vertical-induced fractures. The sections of the borehole between 68.25 to 69.50 m and 77.75 to 78.00 m are intensely fractured, causing appreciable core loss. The remaining portions of the continuous core have fresh schist with low fracture density. The identification of

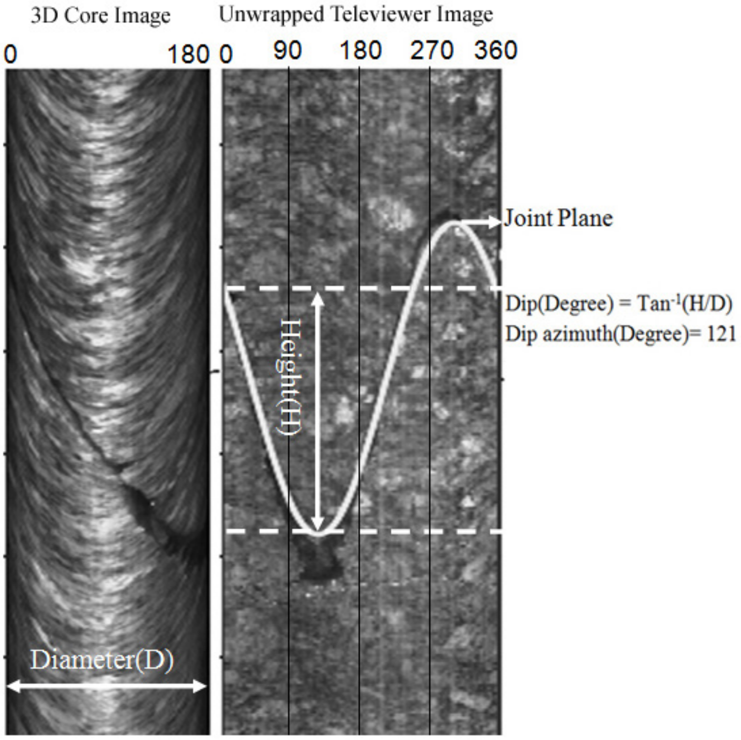


Fig. 3: Structural interpretation of optical borehole imaging log (logs are oriented to the north). The azimuth/direction of structures can be measured directly, while the dip amount can be calculated using the borehole diameter and the height of the sinusoid/feature's height using the formula introduced by Pollok et al. (2018).

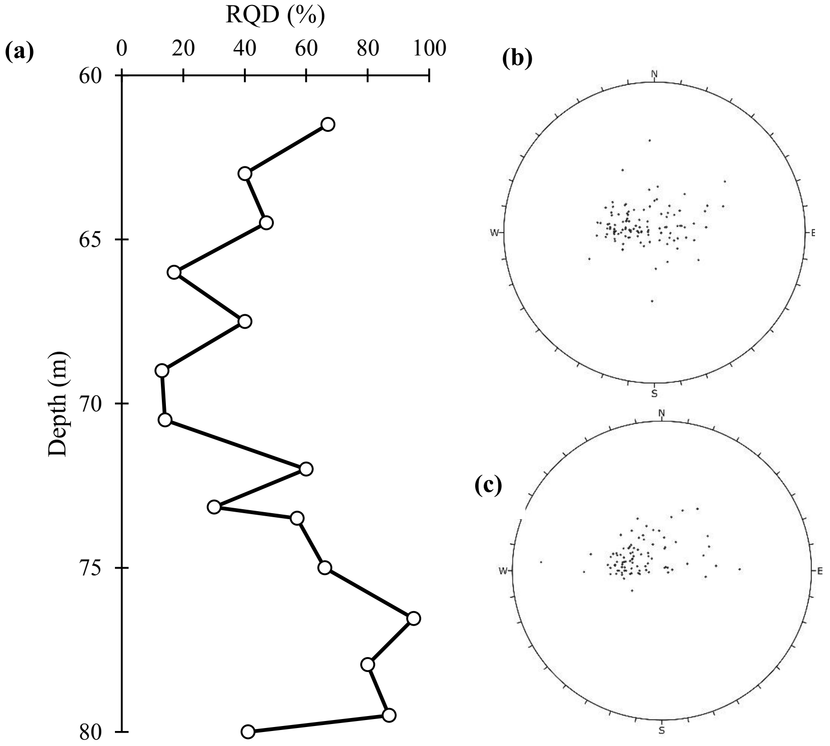


Fig. 4: (a) Graphical plot of RQD as a function of depth, (b) and (c) are equal angle lower hemispheric projection of discontinuity data above and below 70.4 m. Note: the discontinuity density decreases as depth increases. In total 112 discontinuities are present within 60–70.4 m, while only 89 discontinuities are present within 70.4–80 m.

these features, along with the measurement of their spatial orientation, will be discussed in the following sections.

Joint identification and its characterization

Multiple primary and secondary joints are visible in the high-resolution optical televiewer image. The foliations have limited intersections and are usually planar in nature. A total of 279 discontinuities were identified and processed in GeoCAD, including 202 primary joints (foliation planes), 66 moderately dipping secondary joints, and the remaining in-situ fractures. Among all the joints, 182 joints are low angle dipping below 30°, 66 joints are moderately dipping ranging from 31 to 55°, and 20 joint sets are steeply dipping (greater than 55°). The majority of the discontinuity planes are trending towards the southeast and have a low dip angle below 30° (Fig. 5).

Many foliation planes with apertures are observed at different depths. Joint apertures ranging from 2 to 15 mm are occasionally present along joints and foliations at various depths, which were measured by extending the sinusoids within their space. They are particularly present in between moderately dipping southeast to southwest dipping joints. From the beginning of the borehole to the end, primary apertures are developed, with or without alterations. There are no signs of alterations in the joint aperture formed at depths of 61.50 m and 75.08 m, representing residual free aperture (Fig. 6a,b). A washout-formed cavity of around 10 cm in size was found at these depths, indicating the presence of a weak plane parallel to the foliation (Fig. 6c,d). Many foliation plane parallel apertures are observed in optical televiewer logs as a result of groundwater action or washout action of drilling.

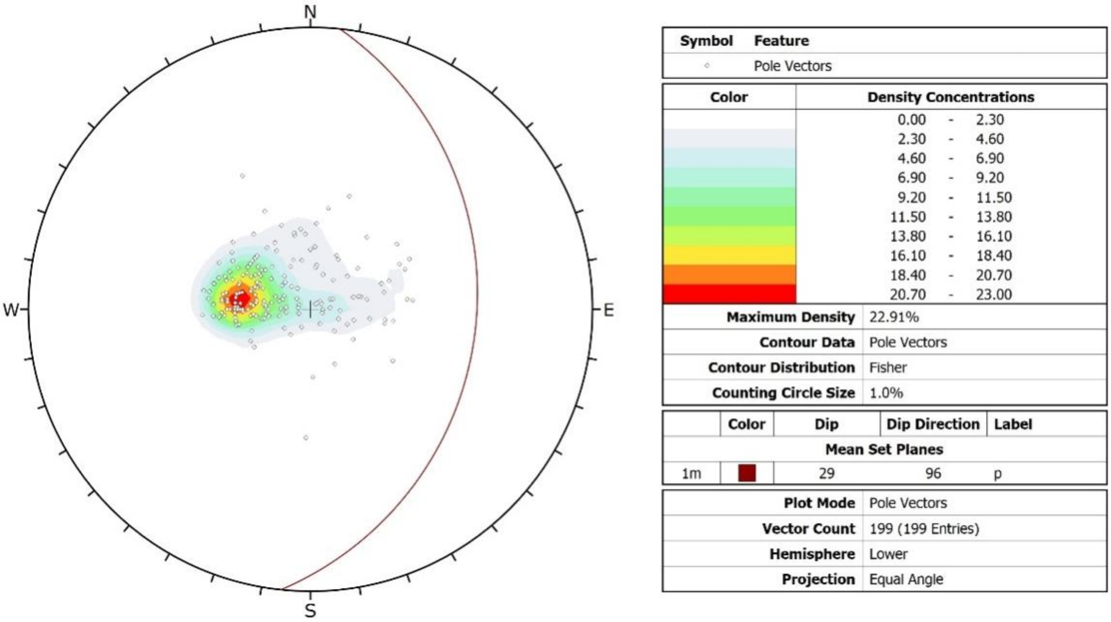
Fracture identification

The network of hairline fractures known as sheet joints, resulting from weathering and uploading, is easily visible in the oriented core image and unwrapped image which can be verified by the cores acquired by the drilling. Due to the ductile nature of the schist, there are fewer geological fractures. Within a 25 m depth interval (from 60 to 85 m), only around 15 fractures were documented, which are referred to as sheet joints. The fracture network is visible only in a few places. For example, at a depth of 69.0 to 69.50 m, a cluster of fractures in this zone includes about 10 natural foliations and numerous minor hairline fractures. At a depth of 74.10 to 74.50 m, a rough and irregular east-west trending vertical to near-vertical fracture was found. Some drilling-induced vertical mechanical fractures are also observed at this depth. Some indistinct random fractures, which are difficult to measure spatial orientation, were visible in OTV images (Fig. 7). Among the 279 prominent discontinuities observed within the 25 m depth interval, only 11 are near-vertical geological fractures.

In contrast, the core extracted from the same image interval displayed a higher number of fractures. Among these fractures, around 10 were geological in origin, with some being open and others filled with minerals. The rest of the fractures were drilling-induced mechanical fractures.

Correlation accuracy

Interpretations such as identification of mineral fills and realistic alteration grades are lacking in the OTV image logs due to features being beyond the resolution of the OTV tool or not imaged due to the fracture mineral fill lacking significant



Symbol	Feature
◦	Pole Vectors

Color	Density Concentrations
⬜	0.00 - 2.30
⬜	2.30 - 4.60
🟦	4.60 - 6.90
🟦	6.90 - 9.20
🟩	9.20 - 11.50
🟩	11.50 - 13.80
🟩	13.80 - 16.10
🟨	16.10 - 18.40
🟧	18.40 - 20.70
🟥	20.70 - 23.00

Maximum Density	22.91%
Contour Data	Pole Vectors
Contour Distribution	Fisher
Counting Circle Size	1.0%

	Color	Dip	Dip Direction	Label
		Mean Set Planes		
1m	🟥	29	96	p

Plot Mode	Pole Vectors
Vector Count	199 (199 Entries)
Hemisphere	Lower
Projection	Equal Angle

Fig. 5: Equal angle lower hemispheric projection of major joint orientations retrieved from OTV image. The majority are of primary joints/ foliation planes indicating that the mean orientation of foliations along the hole dips toward the southeast with an attitude of a mean plane- 96/29.

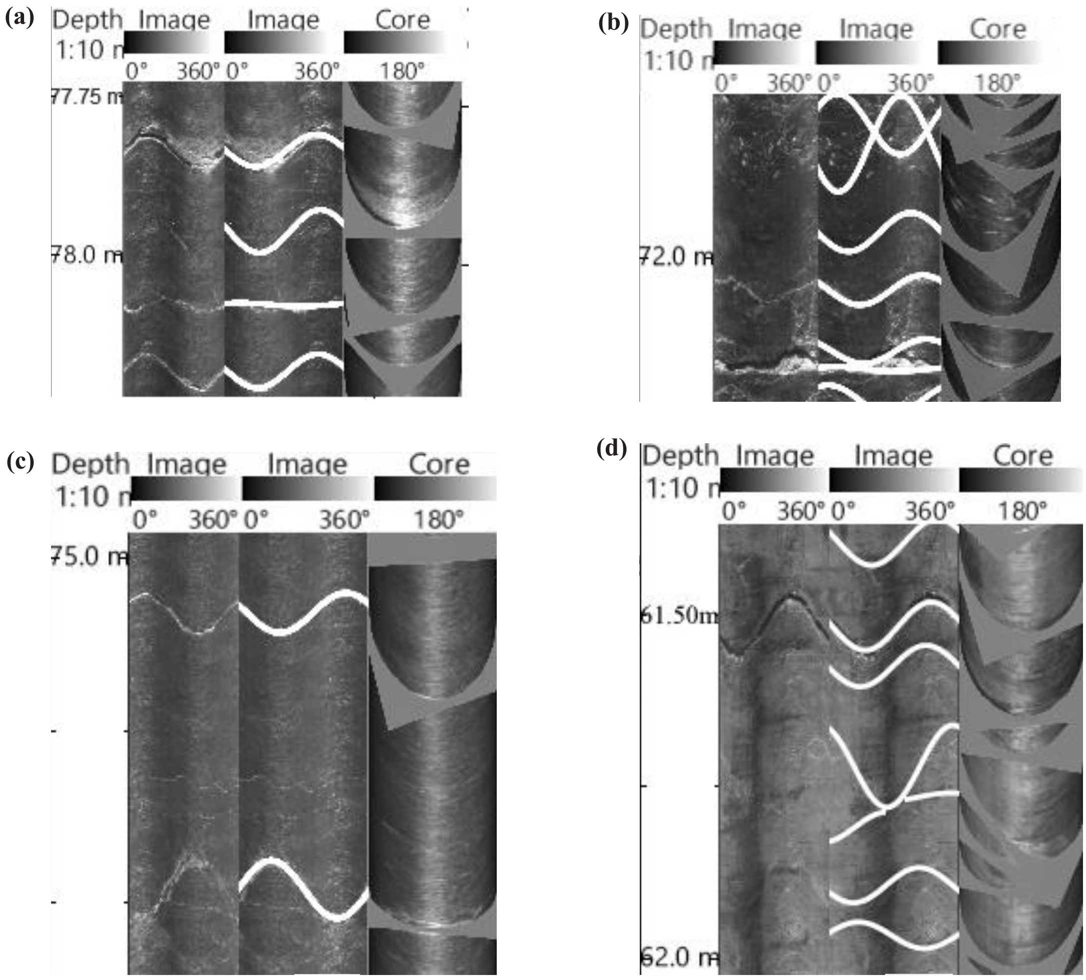


Fig. 6: Joint apertures and foliations observed in OTV images at different depths (a) aperture parallel to foliation, (b) washout formed cavity along aperture, (c) residual-free aperture almost parallel to foliation, (d) residual-free aperture.

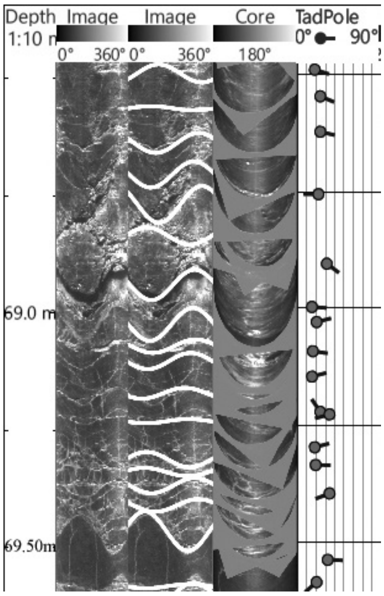


Fig. 7: Weak, intensely fractured zone observed on the OTV image at the depth of 68.5–69.5 m.

contrast to the borehole and absence of drastic changes in mineral composition and lithology. Furthermore, the down-hole image logs reveal several fractures that were not identified in the drilled cores due to core loss (Fig. 8a,b).

One possible reason for this is the presence of crushed or fractured zones, where drilling and movement of the drilled core have caused damage to the point where individual fractures cannot be identified. This is an example of where OTV logs can provide better results than core logs, especially when the core loss is prominent. In contrast, the drilled core reported some vertical fractures induced by mechanical breakage during core spinning while drilling.

Apart from measuring the spatial orientation of discontinuities and the position of actual core loss zones, drilled cores, and OTV logs match with only minor differences. The accuracy of the OTV logs compared to the drilled core suggests that down-hole imaging was performed through stable rock, providing a smooth borehole wall.

DISCUSSIONS

In terms of the Optical Tele-Viewer (OTV) logs, they provide the spatial orientation of structures, making it possible to orient the corresponding intervals of drill cores and visualize in-situ discontinuity field conditions, whereas, for the traditional core logging, the degree of uncertainty caused by measurement of spatial orientation of discontinuities can be as high as 16° for azimuth angle for NQ, 12° for HQ, and 9° for PQ core sizes (Holcombe, 2013).

While in the OTV approach, the combined error in the measurement of dip azimuth of features, including inaccurate picking of features from televiewer logs (error not more than 5°), inaccurate measurement of borehole azimuth while orienting televiewer hardware and taking borehole wall image (error ranging between 0.3 and 5°, with an average of 1°), does not exceed 6° on average (Gwynn et al., 2013), which is much less than that of traditional logging. The vast difference in this uncertainty between manual core logging and OTV logging is due to the negation of the problems of core spin and orientation line markings, and inaccuracy in decision-making while handpicking features and measuring orientation.

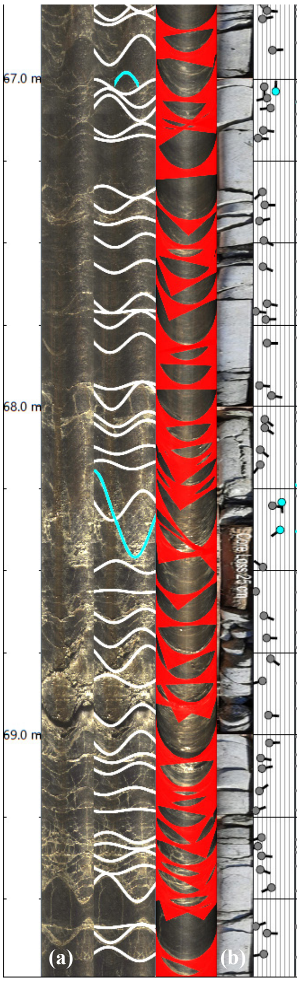


Fig. 8: Correlation between a down-hole optical log and a drilled core log showing an appreciable amount of resemblance in structural interpretation (a) an optical televiewer image, (b) manual core log.

Drilling typically gouges out fractures and increases their apertures (Paillet et al., 1985), as the top and bottom of steeply dipping fractures appear to have greater dip due to the gouge effect (Cohen, 1995). Fracture infillings might be gouged out, making sealed fractures appear open, and closely spaced fractures might be gouged out to appear as a single large zone. In such a zone, the orientation of only the top and/or bottom fracture might be determined. For these discrepancies, the OTV log can represent the actual scenario, as observed in the present case. Here, the OTV log has imaged almost all of the features present, except for the differentiation of mineral fillings, and the measured structural orientations are consistent with real field conditions. Apart from drilling-related gouge effects on incompatible rocks like schist affecting the appearance of OTV images, the structural interpretation from borehole televiewer images in the present study has higher confidence than traditional logging.

CONCLUSIONS

The study attempts to demonstrate the effectiveness of the integration of down-hole optical televiewer imaging (OTV logging) and manual core logging, which has not been explicitly considered yet in the Nepal Himalayas. A case study from the Lesser Himalayas of eastern Nepal is taken as an example to demonstrate its effectiveness.

The combination of OTV logging and manual core logging serves as a pivotal tool, offering both detailed structural data and qualitative strength information. While the OTV log provides key insights such as the orientation of discontinuities, fracture frequency, and apertures, manual core logging complements it by revealing the physical characteristics of the core. This synergy leads to a comprehensive understanding of subsurface conditions, enhancing project feasibility assessments for excavation, underground tunneling, or other construction activities.

Furthermore, the hybrid method overcomes some of the inherent limitations of manual core logging alone. Accurate structural interpretation from a manual core log, often challenged by gravity-induced effects and mechanical errors, becomes achievable. The potential human errors associated with measuring discontinuities and manual logging of recovered cores are mitigated, resulting in a higher level of accuracy. One essential aspect of this combined approach is the precise depth matching of all data, a task that is simplified and rendered more efficiently through coordinated interpretation of core data and OTV logs. The exact location of core loss and weak zones, otherwise ambiguous in physical logs, becomes discernable.

To sum up, it accounts for the fact that the combination of manual core logging and OTV logging provides timely and more reliable in-depth subsurface information on a field scale. From the present study, the expected advantages and effectiveness of hybrid logs compared to the prior manual conventional approach have been proven, which facilitates the introduction of a simple and reliable measure for the geotechnical investigation of the given rock mass. The result obtained in this study should be further validated in different geo-mechanical settings to expand its application.

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