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Comparative Study of Two Geophysical Methods to Investigate the Depth of Weak Zone: A Case Study of Kulekhani-I Hydroelectic Project Dam, Makwanpur, Nepal

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Abstract

The stability of the dam is the most crucial factor in the development of hydropower. Traditionally, surface geological mapping and monitoring of the structure's surface behavior are used for stability assessments and investigations. However, those methods frequently offer insufficient details about the subsurface and the stability of the dam's construction. Although there are various geophysical methods available for subsurface investigation, it is unclear which is best depending on the situation, the available resources, and the time and/or money restrictions. Geophysical methods are thought of as cost-effective instruments to offer continuous subsurface information. In order to assess each method's efficacy in providing geological subsurface information about the evaluation of the weak zone of the earth fill dam structure of the Kulekhani Hydroelectric Project, Nepal, two widely used geophysical methods—two-dimensional (2D) resistivity imaging and Micro Tremor Array Measurement (MAM)—were directly compared. The accuracy of these approaches' conclusions about the depth of the weak zone and field functionality was compared. The outcomes showed that the MAM and the 2D resistivity approaches provide precise subsurface information on dam weak zones.

Keywords: Micro tremor array measurement; Electrical resistivity tomography; Stability; Weakness zone

Introduction

A dam is a wall-like structure or a barrier constructed over a river or creek to hold water and raise its level to form a reservoir. The Kulekhani reservoir, which currently supports 32 MW of Kulekhani II HPP and has an installed capacity of 60 MW for Kulekhani I HPP, is Nepal's only seasonal reservoir for storing water for hydropower generation. The Kulekhani Dam is a rock-fill structure on the Kulekhani River in the Makwanpur District of Nepal's Narayani Zone, close to Kulekhani. A reservoir called Indra Sarobar, which can hold 85,300,000 m3 of water, is created by the 114-meter-tall dam. The dam's crest is 397 meters long and 10 meters broad. The dam's construction started in 1979 and was finished in 1981. This dam is owned by the Nepal Electricity Authority (NEA). According to estimates, the reservoir will last for 100 years, of which 35 have already passed. No overtopping or significant through flow is permitted for the dam due to the distinct spillway section that was developed and built into the structure. The rock fill is completely covered by the randomized riprap construction used to build the dam.

The significant hydrological systems in central Nepal have been severely impacted by the Ml 7.9 Gorkha Earthquake on April 25, 2015. Tensional fractures have also appeared along the crest of the Kulekhani dam as a result of this significant earthquake and its numerous, powerful aftershocks. According to the eyewitness, the waves created by the earthquake struck the free board of the dam's upstream slope, causing tensional cracks along the dam's crest. Our main concern is to determine how deep these cracks go in order to determine the best way to restore the disturbed area.

The aerial extent and thickness of the deposit, the thickness of the overburden, and important geologic connections are all provided by geophysical techniques. Additionally, drilling and other forms of study may miss closely spaced geological changes, so geophysical measures may be used to discover them in places like suspected subterranean channels and the channel formation at the base of any civil engineering construction. Geophysical data may be particularly helpful for delineating the weak zone in dam structure when paired with other surface investigations. However, a variety of geophysical technologies, including electrical, electromagnetic, ground-penetrating radar, and seismic ones, are being utilized in subsurface research [1-3]. Subsurface geological data may be improved by using the right approach. Geophysical methods are often considered the best for determining underground and subsurface structures. This study compared and assessed the two geophysical techniques of two-dimensional (2D) resistivity imaging and 2D Micro Tremor Array Measurement (MAM) for their possible use in the investigation of weakness zones in the dam axis area. The MAM consists of three consecutive steps, which are: obtaining seismic array records; determining surface-wave phase velocities; and estimating an S-wave velocity structure model [4]. The different types of array geometries are discussed by various authors; Forti et al., (2017) discuss the attributes of different array geometrics [5,6]. The recommended survey is isotropic arrays (e.g., circular or triangular) or at least 2D arrays (e.g., L-shaped), with maximum receiver spacing being larger than the desired investigation depth [7]. The most commonly used technique for geological investigation is the 2D resistivity technique, which may identify clay layers, the water table, and the contact between aggregate and bedrock. Due to how simple it is to collect and analyze the data, the 2D-MAM approach, created by the

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Kansas Geological Survey in 1990, is now widely utilized in engineering and environmental applications [8]. The resistivity survey method is one of the oldest and most commonly used geophysical exploration methods [9]. Which can date back to the period of the 90 s and 20 s [10-12] Electrical resistivity tomography (ERT) is a robust and well-consolidated method for near-surface geophysics with a wide range of applications in the geological, engineering, and environmental sciences. Technological advances (e.g., multi-channel arrays, innovative sensors) and novel tomographic algorithms for data inversions have rapidly transformed ERT into one of the most employed geophysical methods [13].

The primary goal of the proposed research is to conduct a subsurface analysis of the earthen dam of the Kulekhani Hydroelectric Project using two different geophysical methods. After the 2015 Gorkha earthquake, longitudinal fissures appeared on the surface of the dam (Figure 1a-c). Based on the electrical resistivity of the materials below the dam surface, 2D ERT is crucial in identifying and assessing the subsurface state for this purpose. The disturbed (settled) layer's resistivity would be different from the undisturbed (compact) layer's resistivity. The boundaries and size of the disturbed zone would be determined based on the change in measured resistivity for various types of materials. Then, similarly, Micro Tremor Array Measurement (MAM) has been proposed for this time to identify and determine the subsurface condition based on the shear wave velocity of the materials beneath the dam surface. The shear wave velocity for different layers is different based on their density contrast. The lower layer is considered to be more compacted in comparison to the upper layers. On the basis of variations in shear wave velocities for different layers of materials, the boundary and extent of the disturbed zone could be identified. Then the final aim of this study is to determine the accuracy of the results obtained from the two geophysical methods, i.e., ERT and MAM.

Study area

The only reservoir-type hydropower plant in Nepal, Kulekhani-I, is situated in Dhorsing, Makwanpur district, at coordinates 27° 3527.33N, 85° 9' 22.13E. The project is located in central Nepal's Makwanpur district, in the region's northeast (Figure 2). The region is then covered with a variety of tiny to large hills and valleys, as well as highly rough terrain. Then, the Palung Khola, which runs from west to east through the watershed, delineates the dam, and several rivers from the north, south, and west combine to form the Palung Khola.

Methodology

Microtremor Array Measurement (MAM)

The main basic methods to determine the phase velocity are the frequency-wave number (FK) method [14] and the spatial autocorrelation (SPAC) method [15]. The study of the dam axis site follows the FK method. The FK method has the potential, in principle, to resolve the phase velocities of the fundamental mode and of higher modes, if any, but its resolution depends on the array geometry, the array size, the properties of the wave field of micro tremors, and the data quality [16]. Hence, the L-shaped geometric array Micro Tremor Array Measurement (MAM) approach was used to map out the dam along its crest in order to achieve the predetermined goals. In Table 1, each MAM point's specifics are listed.

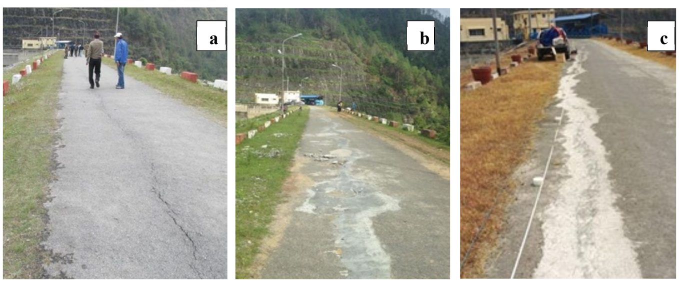

Figure 1: a) Condition of dam crest just after the Gorkha Earthquake b) Condition of dam crest during the field visit July, 2016 c) Present condition of dam crest, 2023

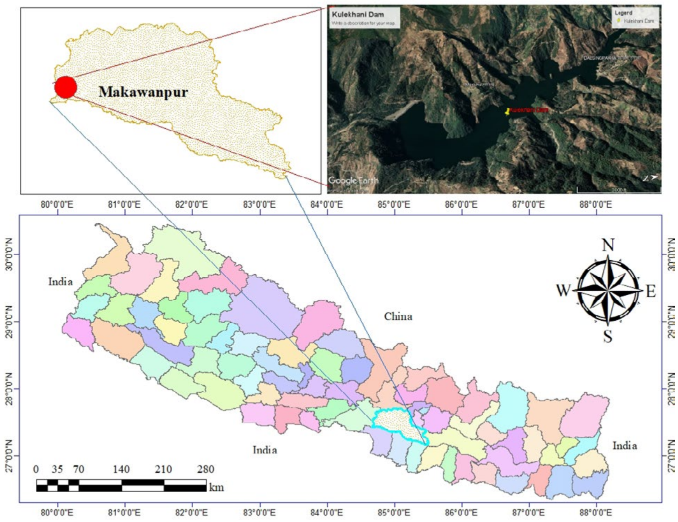

Figure 2: Location of study project

Table 1: MAM survey coverage.

Profile No.	Location	Type
MAM-1	0318039E, 3053104N	L-array
MAM-2	0318011E, 3053140N	L-array
MAM-3	0317947E, 3053169N	L-array
MAM-4	0317954E, 3053198N	L-array
MAM-5	0317931E, 3053217N	L-array

For analysis, two-dimensional (2D) arrays offer the most accurate distribution of data points. A 90-degree angle is maintained between the two legs of an L-shaped array, and both legs are typically the same length. Comparatively speaking to the other 2D array designs, the L-shaped array is simpler to put up in the field. The angles between the two legs of the angular arrays range from 45° to 135°. The resulting vs. profile, where vs. is the typical shear wave velocity, will be an average over the array in each of the 2D configurations. Thus, the center of a created arrangement will match the vs. profile. The length of the profile and the frequency of the waves that were captured determine the scope of the research. According to the area available at the particular site, 24 geophones at a distance of 5 m each were stored. To record the passive waves, vertical geophones operating at 4.5 Hz and equipped with a soundproof pad were employed. While collecting the data, a seismograph was kept at the location where two legs converged. Every site typically had 10 numbers of data captured, with each recording lasting 2 minutes and 32 seconds.

A passive seismic approach called Microtremor Array Measurement (MAM) may be used to determine the 1-D shear wave velocity model for a specific location. The seismograph captures background vibrations (noises) caused by environmental factors including wind, traffic, waves, etc. The word "microtremor" is used differently on each continent.

a. North American passive surface wave

b. Japanese microtremor

c. European Ambient Vibration Waves that are passive are created by:

i. Cultural sources, such as railroads, equipment, and automobile traffic.

ii. Environmental factors like wind, waves, etc.

The sources are randomly distributed and activated during the MAM survey; the direction of wave propagation with respect to the array is unknown; the frequency is lower than that of the active sources; the energy from such sources propagates primarily as surface waves; and the dispersion curve can be extracted from such surface waves.

Data acquisition

Depending on the location and available space, recordings for all 24 channels in the MAM test have been made in both a linear and an L-shaped array. Passive waves from all different sorts of sources may be logged in since there was enough data gathered for a total of 2 m 11 s for each record. The sensor used in this test was a vertical geophone with a natural frequency of 2.0 Hz. Data collection was done with the aid of cutting-edge ABEM Terraloc Pro 2, 32-bit technology.

Data processing

The Georgia Seismic Pro software created by Georgia Technology Corporation was utilized for MAM data processing and analysis (Table 2). Passive surface waves can be processed using SURFACE PLUS. In the F-K, F-V, or F-P domain, where the fundamental and higher-mode dispersion curves are selected interactively, the dispersion spectrum may be determined. Strong forward modeling and a global genetic algorithm (GA) guarantee that inversion will quickly converge. Then, to obtain the profile, the velocity depth profile of each site is inverted. You may understand the underlying strata at each measurement site using this velocity depth profile.

A total of five MAM surveys (L-shaped arrays) were conducted along the dam axis of the first hydroelectric facility in Kulekhani. Here is a description of each MAM along with its associated velocity depth model.

Electrical resistivity tomography

The dam was plotted out along its crest by 2D ERT profiles to achieve these predetermined goals. Table 3 contains information about several profiles. At the dam's crest, ERT profiles were only available along the crest. Riprap and a black-topped road prevented the mapping of profiles over the dam. The positions and lengths of the profiles were determined by surface conditions on the site to cover the required area of investigation.

The depth of investigation depends on the length of the profile and the spacing between electrodes. To collect information from a depth of more than 40 m and deeper, a full length of 300 m is used with a minimum electrode spacing of 5 m. The details of 2D ERT coverage are tabulated in Table 3. Electrical Resistivity Tomography survey is usually conducted following the various arrangements of four electrodes, two currents (A and B), and two potentials (M and N), depending on the specific purpose (Figure 3). Among the four electrodes used with the resistivity meter, two are used to pass the current through, while the other two measure the change in potential. In the Wenner array, the spacing between each of the four electrodes is the same. The amount of spacing can be changed depending on the depth of the survey. The depth of the survey can measure is related to ½ the distance between the outer electrodes. This array is one of the most commonly used [17]. The Wenner configuration was first proposed for geophysical prospecting by Wenner in 1916. The field operation is presented in the photo. Numerous electrode configurations are available for use in ERT field surveys. Both advantages and downsides apply to these arrays. One responds more effectively than the other under certain geological circumstances. Dipole-Dipole and Schlumberger are more effective at mapping lateral changes in structures. Wenner smoothest the image more and appears to have a good signal-to-noise ratio. Numerous considerations must be taken into consideration while selecting an electrode array for the survey in question. In its research the ease in handling were used.

Ease in handling

Gradient and pole-pole arrays are simpler to manage, as was already indicated. On the profile, just two electrodes must be moved. Moving three electrodes in a Pole-Dipole array and moving all four electrodes in Wenner, Schlumberger, and Dipole-Dipole arrays complicate the handling of additional electrodes. However, after the cable has been put out, there is no need to move it for multi-core cables with take outs at a predetermined distance and automated equipment with switchers. Our technology automatically alternates between electrodes, making it feasible to get data for electrode spacings of 5, 10, 15, 20, 25, and so on up to 95 m, which is virtually impossible with manual equipment.

Data acquisition

The quality of data collected in the field is influenced by the terrain, geological setting, measurement density, and instrument and accessory

Table 2: List of MAM ID along with their respective location and coordinates.

S. No	MAM ID	Location	Coordinates of Centre Point	
			Easting	Northing
1	MAM -1	Dam Axis	318039	3053104
2	MAM -2	Dam Axis	318011	3053140
3	MAM -3	Dam Axis	317947	3053169
4	MAM -4	Dam Axis	317954	3053198
5	MAM -5	Dam Axis	317931	3053217

Table 3: 2D ERT survey coverage.

Profile No.	Location	Length (m)
ERT-1	Right side of the dam axis road (towards upstream slope).	300
ERT-2	Right side of the dam axis road (towards upstream slope).	300
ERT-3	Right side of the dam axis road (towards upstream slope).	300
ERT-4	Left side of the dam axis road (towards downstream slope).	300
ERT-5	Left side of the dam axis road (towards downstream slope).	300
Total		1,500

Figure 3: Google map view of Kulekhani dam axis with MAM locations. Previously conducted ERTprofiles have also been shown in this figure.

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quality. Geological variation and surface topography both produce very diverse circumstances. The arrangement of the profiles and fieldwork planning are frequently based on topographical maps. To acquire continuous coverage of the subsurface along the line of research, field data were obtained. The Wenner electrode arrangement was used in the current investigation, as was already described. The focus of the current investigation is the man-made rock-filled dam.

Data quality

Field data are affected by various sounds from various causes. The level of effect is determined by the caliber of the tools and accessories, the data collection techniques, and the topographical and geological setting. Choosing the right tools, add-ons, and data collection system is essential for collecting accurate field data. The area's geological and morphological configuration, together with the proper choice of the profiles' orientation, aid in the detection of noise. The depth and resolution of the subsurface are taken into consideration while choosing the electrode layout. While some electrode configurations give high levels of signal but poor resolution, others produce low levels of signal but better subsurface resolution. The degree of noise rapidly rises as the distance between the transmitting and receiving electrodes increases. The sounds are made through capacitive coupling, induction, telluric radiation, and cultural influences. High quality accessories and the ability of the receiver electronics to handle signals are required to prevent this negative impact on the receiving signal. It is important to realize that sideways scanning is done by geophysical methods in addition to looking vertically and laterally along the profile. The results are also influenced by geological changes that occur inside the radius of effect in a sideways manner. Such impacts could clog the section and make it impossible to comprehend it in a meaningful way. Therefore, geological noises are those sounds that the geological setting introduces into the data but that are difficult to analyze.

Data processing and interpretation

The program, RES2DINV, was used to filter, analyze, and handle the submitted data. However, preliminary data processing was done in the field itself by an experienced geoscientist in order to assess the quality of the obtained data. The software reverses the field data, determines the appropriate resistivity model, and outputs resistivity contours as the result. To create the lithological and geological information, inversion data is employed. The sections above have previously covered the fundamental idea underlying the relationship between resistivity measurements and lithology and geology. Presenting the inversion findings with interpretive cross sections of all 25 profiles for the resistivity model. The resistivity contour value of the ERT result is used to extract geological and lithological information, which is then noted in the appropriate ERT sections. Since the electrodes are installed at each 5 m slope distance (not a horizontal distance or plan distance), the sections are made according to topographic undulations.

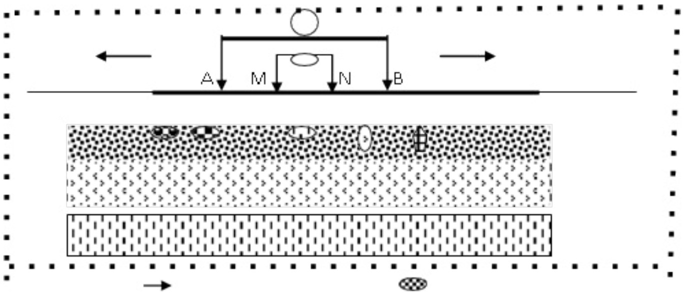
Result of the Study

Microtremor Array Measurement (MAM)

According to the information gathered from the field, all the data were pooled for each site before inversion, and a velocity depth profile for each profile was built using the Surface Plus program produced by Geogiga Technology Corporation. Figures 4-8 provide depth velocity models for each MAM in order to identify the weak layers based on the measured shear wave velocity.

1. MAM-1 (M-1): coordinates: 0318039E, 3053104N

The velocity depth model for M-1 suggests different layers of earth



Electrodes shifting in this direction Inhomogeneity in the overburden (A and B are current electrodes and M and N Are Potential electrodes)

Figure 4: Wenner Electrode Array for profiling

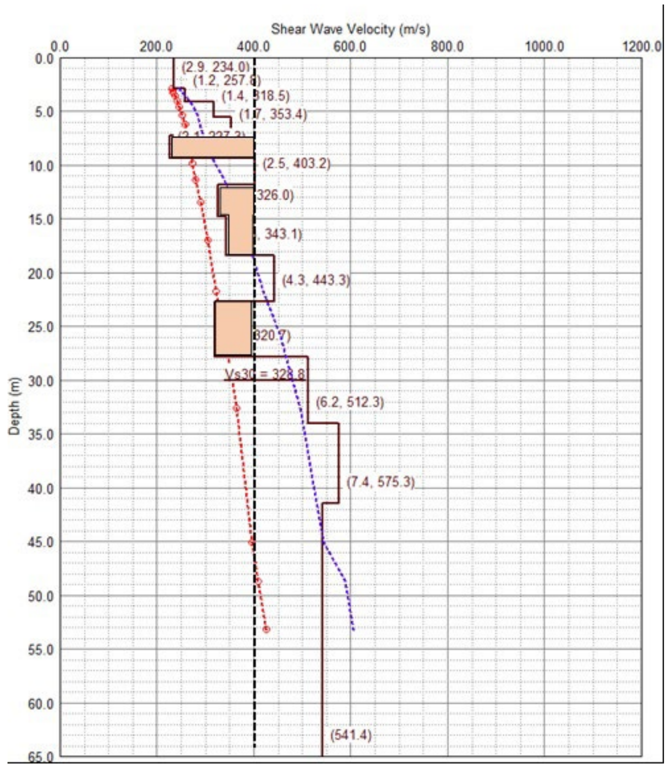


Figure 5: Velocity-Depth model of MAM-1 located at middle part of Kulekhani 1st dam axis.

materials of varying densities therein. In general, the density of the material at the deeper section is greater than the density of the material at the upper section. Most of the layers at the earthen dam were hard-compressed enough at the time of construction. So, a dashed line at 400 m/s has been marked into the velocity depth model to distinguish the loose and medium-density layer from the hard.

Compacted layer

The shaded regions in the figure represent the loose and medium-density layers. Shear wave velocities less than 400 m/s in these regions have probably been generated due to the lower density of those layers resulting from any sort of disturbance. Thus, we can conclude that the section up to 28 m below the surface has been disturbed due to the strike of a wave generated by the 2015 Gorkha Earthquake at this location.

2. MAM-2 (M-2); coordinates: 0318011E, 3053140N

The M-2's velocity profile showed that there were many strata with various densities. The variable density of the materials in the mapped-

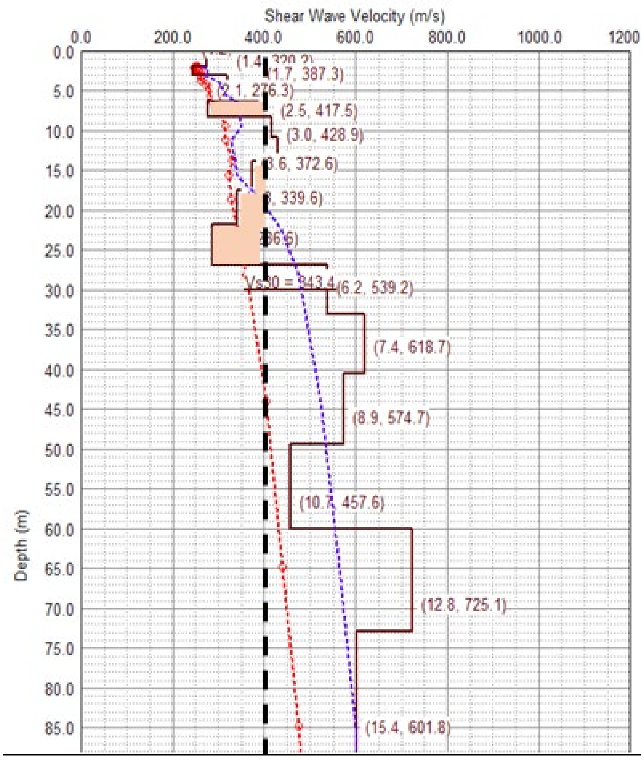


Figure 6: Velocity-Depth model of MAM-2 located at Kulekhani dam axis.

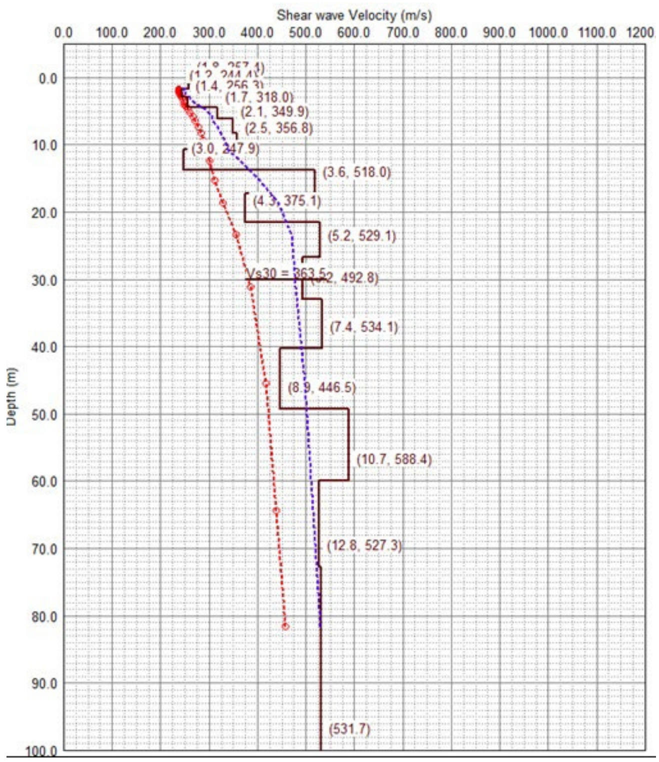


Figure 7: Velocity-Depth model of MAM-3 located at Kulekhani dam axis.

out zone has caused variations in shear wave velocity (Vs). Shear wave velocity is less than 400 m/s in the shaded area of the velocity depth model, indicating a loose and medium-density layer. It is evident that during dam construction, the strata up to 27 meters should have been sufficiently hard-compressed, yet the model has revealed loose

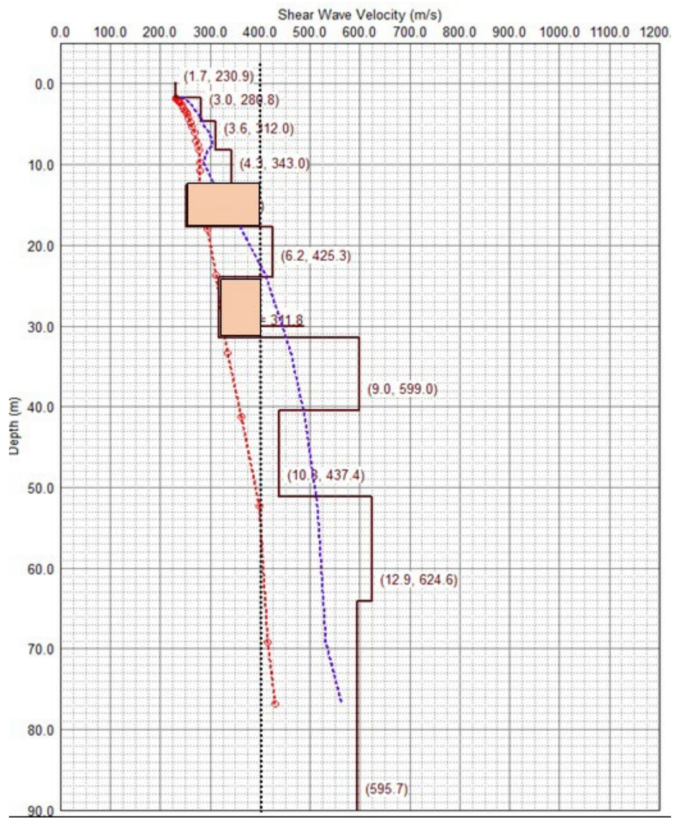


Figure 8: Velocity-Depth model of MAM-4 located at Kulekhani Dam axis.

and medium-density layers. This low-Vs section may have formed as a result of those layers becoming looser as a result of an earthquake disturbance. This velocity depth model has demonstrated that there is disruption at this position up to 27 meters from the dam axis.

3. MAM-3(M-3); coordinates: 0317947E, 3053169N

The velocity depth model for MAM-3 has also depicted different layers of different densities deciphered from different shear wave velocities. The shear wave velocity keeps on increasing up to 10.5 m in a regular way, and then suddenly decreases for the section from 10.5 m to 13.7 m. Similarly, the section from 17.5 m to 21.5 m also contains vs. less than 400 m/s, indicating a loose layer therein in comparison to the upper and lower layers. Thus, it can be concluded that the section up to 21.5 m in this location has been disturbed due to the Gorkha Earthquake.

4. MAM-4 (M-4); coordinates: 0317954E, 3053198N

Based on the various densities, the Velocity Depth Model for MAM-4 has also interpreted several layers. Two strata—12.3–17.8 m and 24–31.5 m—possess shear wave velocities below 400 m/s, indicating that they are loose to medium-density layers. From the top of the Kulekhani earthen dam, it appears that the quake's disruption may be observed at this location down to a depth of 31.5 meters.

5. MAM-5 (M-5); coordinates: 0317931E, 3053217N

The rightmost portion of the crack visible on the dam axis was the location of the velocity depth model for MAM-5, which also disclosed several layers of materials depending on the density contraction. Based on the shear wave velocity, the less compressed layers are distinguished from the tightly compacted ones. Layers with vs. lower than 400 m/s are classified as either loose layers or medium-density layers. At 4.5–6.3

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m and 8.0–21.8 m, respectively, these loose and medium-thick strata may be seen. We infer that the strata up to 22.0 m deep from the dam axis have been somewhat disturbed based on the shear wave velocity values within the various layers.

Electrical resistivity tomography

The model sections obtained from data inversion are presented as resistivity tomogram sections. These tomogram sections show the variation of modeled electrical resistivity in depth and along the line of investigation. These variations in modeled physical properties have a relationship with the subsurface geological and hydrogeological setup. Representative resistivity tomogram sections for each section and their interpretations are presented in Figure 9-11. On the basis of the profiles taken and their sections obtained after the data processing, interpretation has been described under two subheadings only: towards the upstream slope and towards the downstream slope.

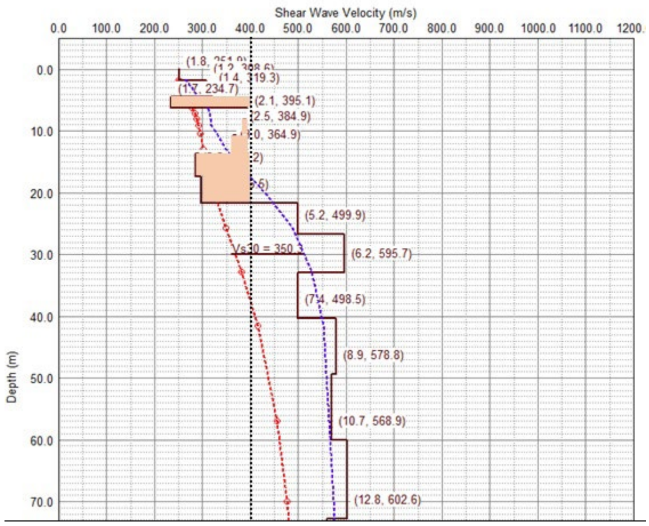

Figure 9: Velocity-Depth model of MAM-5 located at Kulekhani Dam Axis.

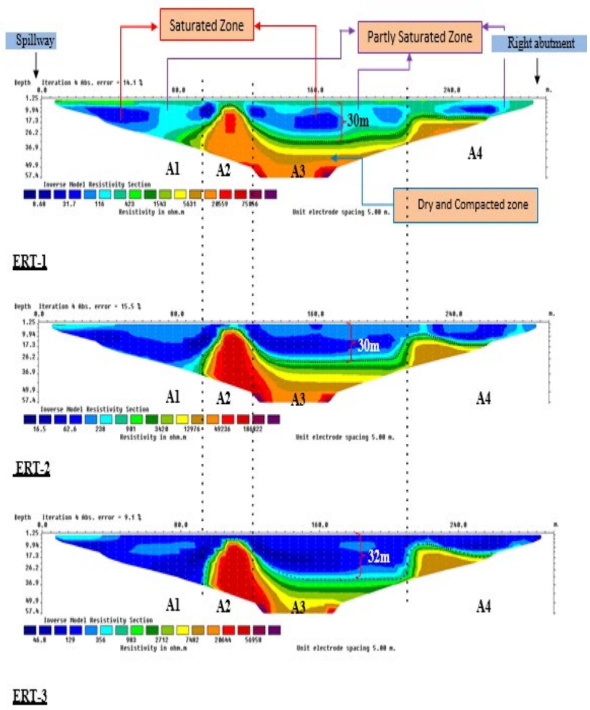

Figure 10: ERT profiles (ERT-1, ERT-2 and ERT-3) towards upstream slope of Kulekhani dam. A1, A2, A3 and A4 represents four areas having variation in resistivities with respect to depth.

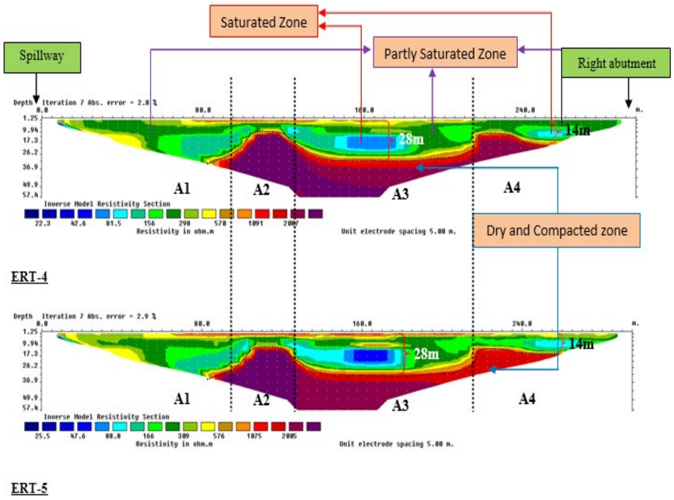

Figure 11: ERT profiles (ERT- 4 and ERT-5) towards downstream slope of Kulekhani dam (from the centre of the dam axis). A1, A2, A3 and A4 represents four areas having variation in resistivities with respect to depth.

- Towards upstream slope (from the center of the dam axis)
- Resistivity Tomograms and their interpretations

Three profiles named ERT-1, ERT-2, and ERT-3 were taken towards the upstream slope of the dam from the center of the dam axis. The tomographs of these three sections obtained after the processing resemble each other. This is why the interpretation of these three sections has been described in a combined form.

ERT-1, ERT-2, and ERT-3 have shown that there are three distinct zones: the saturated zone having a resistivity below 50 ohm/m, the partly saturated zone having a resistivity of 200–500 ohm/m, and the compacted zone having a resistivity greater than 1,000 ohm/m. Four distinct areas have been observed from these three tomographs; (starting from spillway) 0-95 m (A1), 95 m–120 m (A2), 120 m–215 m (A3), and 215 m–300 m (A4).

Area A1 is expected to have been disturbed by the earthquake itself, and the wave formed as a consequence of this earthquake up to a depth of 30 m. But Area A2 seems strong enough that the effect of the earthquake is not significant. This area seems to be compact enough. Area A3 from 120 m to 215 m from the spillway seems to be critical in terms of its strength. Cracks observed at the surface of the dam crest also reinforce this statement. From the analysis of the tomographs, this zone is expected to get disturbed up to a depth of 30 m. Whenever we go towards the center of the crest, the effect has been observed a bit deeper than in the peripheral sections (ERT-Figure). By this calculation, the top 35 m of Kulekhani dam seems to be disturbed by the earthquake and its consequences. The layer below 30 m in this section is consolidated enough, which is verified by the high resistivity of the underlying layers. Successive layers below this depth have increasing resistivity, thereby indicating more compactness. Water percolating through the cracks on the crest surface might have affected up to this 30 m depth only. This verifies that the Gorkha Earthquake and its consequences have affected the top 30 m of the Kulekhani rock fill dam. Though area A4 does not seem to be so critical at the surface, the effect of the Gorkha Earthquake has been expected up to a depth of 12 m.

Towards downstream slope (from the center of the dam axis)

Two profiles named ERT-4 and ERT-5 were undertaken towards the downstream slope of the dam from the center of the dam axis. Spillway has been taken as a reference point. These profiles were also taken next to the spillway, starting with the first electrode adjacent to the spillway and the last electrode towards the right abutment of the dam. The two tomographs obtained after the data processing in the lab are somehow similar to each other, so they have been described under the same subheading.

ERT-4 and ERT-5 have shown that there are also three distinct zones: the saturated zone having a resistivity below 50 ohm/m, the partly saturated zone having a resistivity of 200–500 ohm/m, and the compacted zone having a resistivity greater than 1000 ohm/m. Four distinct areas have been observed from these two tomographs; (starting from spillway) 0-95 m (A1), 95 m–120 m (A2), 120 m–215 m (A3), and 215 m–300 m (A4).

Two distinct saturated zones have been observed at a distance of 160 m and 250 m, respectively, from the spillway in both tomographs. Likewise, in the previous sections (ERT-1, ERT-2, and ERT-3), anomalous resistivity has been observed in area A2. A partially saturated zone has been observed in all other areas of these ERT sections. A dry and compacted zone has been observed in both sections below 28 m, thereby indicating distinct resistivity variation. The black dotted line indicates the boundary between the disturbed and non-disturbed layers within the dam.

Area A1 (up to 95 m from the spillway) is supposed to have been disturbed by the earthquake itself, and the wave formed as a consequence of this earthquake up to a depth of 30 m. Area A2 in both profiles has shown anomalous resistivity in a dome shape compared to its peripheral area. The zones on the right and left of this zone are partly saturated. The maximum depth of the earthquake's effect is 28 m at the middle portion of the Kulekhani dam (Area A3), whereas 14 m only after 215 m.

Discussion

Along the Kulekhani Dam axis, five (5) MAM surveys of an L-array configuration were conducted. MAM-1 was conducted at the middle of the dam axis, and the others were moved toward the right bank of the dam at roughly the same intervals. The depth of disturbance according to MAM sites (Table 4).

Table 4: The depth of disturbance according to MAM sites.

MAM ID	Depth of Disturbance Observed (m)
MAM-1	28
MAM-2	27
MAM-3	21.5
MAM-4	31.8
MAM-5	22

This survey has shown that the upper 32 m segment of the dam is the only part where there is dam disruption. Since the shear wave velocity doesn't abruptly shift after 32 m, the bottom layers appear to be fine.

Five total ERT profiles were collected along the dam axis. Two profiles (ERT-4 and ERT-5) were positioned towards the downstream slope of the dam, while three profiles (ERT-1, ERT-2, and ERT-3) were located towards the upstream slope of the dam (from the canter of the dam). All five of these profiles were 300 meters long, which is adequate to map out the dam's most affected area. Significant surface fractures have been seen between 40 and 200 meters away from the spillway.

Three tomographs obtained after data processing for ERT-1, 2, and 3 are quite similar as they were taken adjacent to each other along the dam. These sections have shown that there are dome-shaped features with a high resistivity value greater than 1000 ohm/m at a distance of 95–120 m from the spillway, indicating that this 25-meter section is strong enough. An initial section of 95 m from the spillway has been observed to have been disturbed up to a depth of 30 m. Likewise, the section from 120 m to 215 m (95 m in length) from the spillway has been observed to get disturbed up to a depth of 30 m from the surface. Although the black-topped road prevented the ERT study from being performed at the dam's central axis, it is believed that the dam was disturbed to a depth of 32 meters. However, the impacted depth in the part beginning at 215 meters is just 14 meters. This outcome demonstrates that the left and center portions of the dam were more significantly impacted by the earthquake.

The results from the ERT-4 and 5 tests have likewise been comparable. The first 95 meters from the spillway were found to have been disrupted up to a depth of 30 meters. However, the 95- to 120-meter part with the high resistivity value (> 1000 ohm/m) appears to have been unaffected and strong enough. The earthquake was felt up to a depth of 30 meters in the 95-meter stretch from 120 meters to 215 meters that is directly adjacent to this intense area. The portion has only been impacted up to a depth of 14 meters, starting at 215 meters.

Conclusion

The most important element in the development of hydropower is the dam's stability. For stability evaluations and investigations, surface geological mapping and monitoring of the structure's surface behavior are often utilized. These approaches, however, typically provide insufficient information on the subsurface and the stability of the dam's design. Although there are several geophysical techniques for subsurface study, it is uncertain which is optimal given the circumstances, the resources at hand, and the time and/or financial constraints. Geophysical techniques are regarded as efficient tools for providing ongoing subsurface data.

Two widely used geophysical methods—two-dimensional (2D) resistivity imaging and Micro Tremor Array Measurement (MAM)—were directly compared in order to evaluate each method's effectiveness in providing geological subsurface information about the evaluation of the weak zone of the earth fill dam structure of the Kulekhani Hydroelectric Project, Nepal. Comparing the findings produced by different methods on the breadth of the weak zone and field functionality. The results demonstrated that the 2D resistivity technique and MAM both offer accurate subsurface information on dam weak zones.

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