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Epigenetic Gorges and Their Treatments for Dam Safety: Case from Kundghat Dam, District Jamui, Bihar, India

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Abstract: A major engineering challenge was encountered during the construction of the Kundghat Dam in Bihar, India. During excavation for the dam's foundation, a buried river channel (paleo-channel) was discovered. The paleo-channel, or epigenetic gorge, was a deeply eroded trench in the bedrock filled with highly permeable materials and proved to be a significant geological surprise. This geological feature posed two major threats: first, potential leakage due to the porous nature of the paleo-channel material, and second, settlement within such deposits. To ensure the dam's long-term safety, a series of grouting techniques was implemented to reduce the permeability of the paleo-channel material. The remedial measures included row grouting, grout curtains, and Tube-à-Manchette (TAM) grouting, a specialized method that allows multiple, controlled injections into the same area to achieve thorough material consolidation. The use of these advanced grouting methods successfully stabilized the dam's foundation, mitigated the risks associated with the paleo-channel, and ensured the structural integrity of the Kundghat Dam.

Keywords: ***Epigenetic gorges, Paleo-channel, Peninsular shield, Dam foundations, Dam safety.***

Introduction

Epigenetic gorges (or paleo channels) are formed when channels that have been laterally displaced incise down into the bedrock of the former valley. These Valley-filling events that promote epigenetic gorges may be localized or widespread. The term 'epigenetic' refers to the secondary nature of the bedrock gorges, which occur after the formation of the original gorge and are the result of lateral shifting of the channel by landslide debris, alluvial fans or widespread fluvial aggradations (Engeln von, 1942; Pant, 1975). Epigenetic gorges are valleys carved by a river that cut down through a new, often younger, layer of rock into an older, underlying geological structure. These gorges offer insights into the complex history of a landscape by showing how rivers can maintain their course despite changes in the geology below. This process is a result of the combined forces of erosion, the underlying geology, climate and tectonics. The paleo-channels or fossil valleys may also be the result of aggradations in response to climate change scenarios or fluctuating base-level situations. Epigenetic gorges have been well recognized in fluvial landscape regimes all around the world.

Paleochannels within dam foundations present substantial challenges due to their potential for increased permeability, which can lead to seepage and internal erosion. The paper presents a case of a paleo-channel in Kundghat dam foundation and its mitigation.

Kundghat dam project envisages construction of a 39.583m high earth dam across the Bahaur River, to impound a gross water storage of 8.76 million cubic meters at full reservoir level of 126.6 m for harnessing the available water resources of the Bahaur River up to the optimum. The project components also involve constructing a 5.88 km long main canal with a head discharge of 3.2 cusec. The main canal and its distribution system shall provide annual irrigation to 2035.47 ha catchment command area (CCA).

A 351 m Cut-off Trench (COT) along the dam axis with a grout curtain was designed as a principal measure for seepage control. The geological log of the COT reveals the presence of bedrock between 7 m and 14 m. However, the presence of a deep epigenetic gorge/paleo-channel between chainage 110 m and 165m was a geological surprise that poses a threat to the dam's safety. This feature is concealed and was not picked up during investigations.

Geological and geomorphic set-up of the site

Physiographical set-up of the area around the Kundghat dam site shows a diverse landscape of Jamui hills and east-west trending Burwa ridge, plateaus, erosion structures and river terraces. The Bahaur River near the dam axis flows towards a northwesterly direction, and after flowing about 400 m takes a northerly swing. In general, the area is characterized by distinct east-west trending hills comprising mainly quartzite with subordinate schists. The area exposes rocks of Chhotanagpur Gneissic Complex (CGC) wherein mainly quartzite with subordinate schists is exposed. The major distinctive litho-tectonic domains of the CGC in the area are the Rajgir– Munger metasedimentary Belt and Bihar Mica Belt. The metamorphic of Chotanagpur Mica Belt mainly comprises quartzites, mica schist and amphibolites (Lower to Middle Proterozoic), while

Munger Group comprise quartzite and phyllites (Middle Proterozoic) and granites, gneisses and migmatites, meta-dolerite and amphibolites and pegmatites (Upper Proterozoic). The Bihar Mica Belt encompasses mainly in Nawada, Jamui and Banka districts.

The Bahur River at the dam site flows from a southeasterly direction to a northwesterly direction, and the dam axis is N50°E-S50°W. The rocks exposed in the dam site area are quartzite with subordinate schists mainly on the right flank, which has a steeper slope, while on the left flank, River Borne Material (RBM) admixed with slope wash is present between the steep slope and the river course. The riverbed section is devoid of rock exposure; however, boulders and pebbles of quartzite with coarse to medium-grained sand occupy the river section.

The general trend of foliation in quartzite with subordinate schist partings trend N75^{0}W-S75^{0}E with sub-vertical dips (steep) in southwesterly direction in the right flank of the dam axis, whereas the dips are moderate (45^0-60^0) on the left flank of the dam axis. This variation may be attributed to regional folding in the rocks.

Tectonic uplift and climatic variability of epigenetic gorges

The presence of epigenetic gorges is an intriguing type of geological configuration with major implications for understanding the relationship between climate and tectonic activity. These deep, narrow gorges, carved by a river through a bedrock ridge that was buried by sediment, provide valuable insights into past landscape conditions.

Tectonic events, such as a localized uplift, can alter drainage patterns and create the conditions necessary for epigenetic gorge formation. The concept of antecedence is particularly relevant, where a river maintains its course as the landscape slowly rises around it due to tectonic forces. The river's ability to erode downward keeps pace with the uplift, resulting in a gorge. While not always a sign of ongoing tectonics, the presence and characteristics of these gorges can indicate past tectonic events. There are a few studies from the northwest and Central Himalaya where their formation mechanism and climate–tectonic significance have been highlighted (Pratt-Sitaula et al., 2007). Climate plays a crucial role in the gorge formation of gorges' aggradation and incision phases. Changes in precipitation or temperature can drastically affect a river's sediment load and discharge. For instance, a period of increased erosion due to a wetter climate can lead to the widespread deposition of sediment, burying the original valley. Conversely, a change to a drier climate might reduce sediment supply, enhancing the river's ability to incise and carve into the underlying bedrock.

The formation of epigenetic gorges and fossil valleys (the old, now-buried river channels) is a direct outcome of this climate-tectonic interaction. Studies in the Himalayas (Chakraborty et al., 2017) have shown that while the location of these gorges is often structurally controlled, the abandonment of the old river courses was a climatically induced event (Figure 1). The sediment filling the valleys can be dated to specific climatic periods, providing a timeline for these landscape changes. While not always directly indicative of ongoing tectonics, the presence of epigenetic gorges may be related to past tectonic events that caused uplift or altered drainage patterns. Climate change can significantly influence sediment production and transport in river systems.

Several mechanisms can lead to the formation of these intriguing landforms, viz., river capture, obstruction and diversion, such as landslide dams/paleo-landslides, and antecedence that refers to the existence of the river prior to the tectonic uplift episode, etc. The bedrock geometry affects the location and lateral mobility of an incising channel, whereas the original valley shape determines rates of bedrock incision (Ouimet et al., 2008).

In terms of the processes point of view, (i) before valley fill aggradation (in the present-day fossil valleys), the rivers were sediment-limited, and thus the ambient stream power was used to incise the channel (Fig.1). This probably happened because. (ii) The rivers did not migrate laterally to their present course (epigenetic gorge), as observed in cases of landslide-dam river courses (Ray and Srivastava, 2010). Landslide dams are also one of the major causes to change the river courses and to facilitate the formation of epigenetic valleys.

Geological challenges of epigenetic gorges in dams

The challenges associated with epigenetic gorges in the context of storage dams relate to their geological and hydraulic implications, potentially affecting dam safety and reservoir management. These channels can pose significant implications for dam construction and stability, including structural Integrity, water leakage and sediment management, etc., which may impact the lifespan of the dam and its reservoir. It is, therefore, imperative to conduct thorough geological assessments to identify such channels and evaluate their impact on the safety of dams.

Most epigenetic gorges documented in the literature occur about landslide dams, including examples from the northwest Himalaya along the Indus River (Hewitt, 1998), Central Nepal along trans-Himalayan rivers (Korup et al., 2006; Pratt-Sitaula et al., 2007).

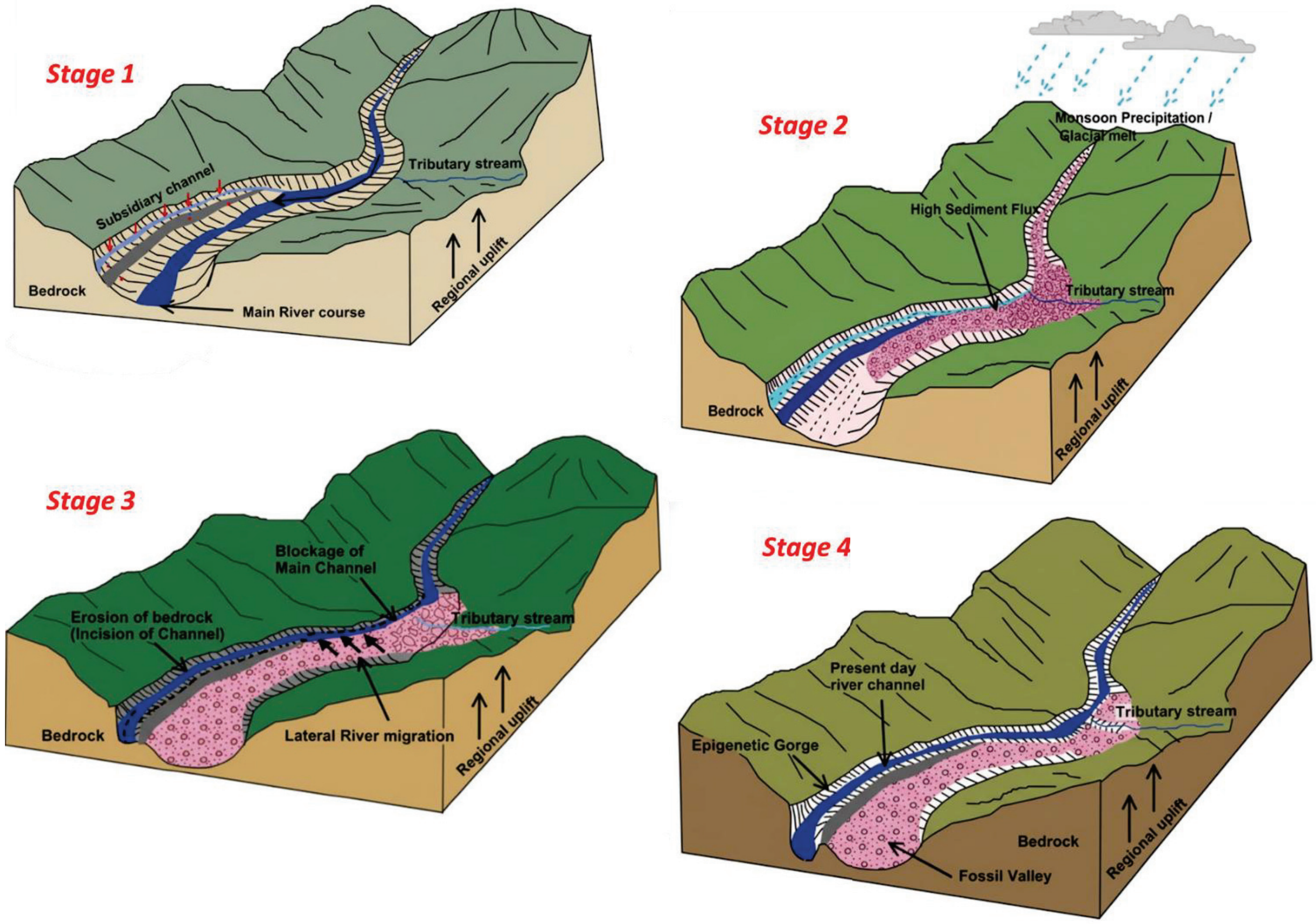

Figure 1, Block diagrams showing evolutionary stages of fossil valleys and associated gorges (modified after Kothyari and Juyal, 2013). Stage 1: Position of the river channel. Stage 2: Major valley fills aggradations occurred (during the early Holocene) climatic optimum. Stage 3: Enhanced sedimentation that led to the lateral river migration, thus occupying the subsidiary channel, and Stage 4: Present River course flowing through the gorge section.

The prime components of paleo-channel sediments are gravel and sand deposits, and their porosity, distribution of water and salt, and modifying transport, as well as high permeability, which act as subsurface conduits (Triantafilis and Buchanan, 2009). The permeable properties of the paleo-channels have created major concern due to the loss of irrigation water through deep drainage (Wray, 2009). The challenges posed by saturation of buried channels (or fossil valleys) have been recognized (Chakraborty et al., 2017) as an abnormal increase in the groundwater table, washing out of fines from the outlet, land subsidence due to saturation, decrease in reservoir storage capacity and weakening of abutment, etc.

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Depending on the post-depositional environment, paleo-channels may be exposed to the surface or buried. Such a channel is no longer part of an active river system and generally remains scaled to the channel's flow. Paleo-channels are ancient riverbeds or stream valleys buried or abandoned over time, often concealed in shield (a case of Kundghat dam) and desertic areas. Identifying probable paleo-channels in peninsular terrain is challenging, where slope variation is minimal and geomorphologic signatures are often obscured. The potential challenges include

i. The bedrock erosion rates in epigenetic gorges can be very high and variable. This could lead to unexpected changes in the riverbed and surrounding geology near the dam and reservoir

ii. The formation and evolution of epigenetic gorges can influence sediment transport and deposition patterns in the river and reservoir, potentially impacting reservoir capacity and dam operation.

iii. The steep, often narrow nature of epigenetic gorges can affect the stability of the valley slopes surrounding the reservoir, potentially increasing the risk of landslides into the reservoir.

iv. If a dam is built within or near an epigenetic gorge, the geological structure and ongoing erosion could challenge the long-term stability and integrity of the dam's foundations.

v. The altered river course and incision rates associated with epigenetic gorges can change the hydrological regime of the river, potentially affecting water flow patterns into and out of the reservoir, and

vi. Designing and constructing dams in areas with complex geological features like epigenetic gorges can present unique engineering challenges, requiring thorough site investigation and specialized construction techniques.

In the Himalayan and Trans-Himalayan region, deep-buried channels/fossil valleys at many projects like Parbati HE Project Stage-II, Nimmo Bazgo hydroelectric Project, etc., have been identified during investigation stages (Chakraborty et al., 2017). These deeply buried channels pose significant challenges to the safety of the project. Paleo-channels in peninsular areas were formed due to river migration driven by neo-tectonic activity and monsoonal shifts during the Holocene period. The presence of faults and lineaments in the basin has influenced both the river's path and the location of these paleo-channels.

A variety of techniques have been used to map paleo-channels; mostly ground-based geophysical techniques including gravity, seismic and electrical methods, followed by drilling explorations. However, a preliminary assessment can be made by careful reconnaissance of topographic, geologic and geomorphic features and detailed engineering geological mapping of the dam site area.

To avoid problems due to paleo-channels concerning dam foundations, it is important to identify the buried channel at the investigation stage itself so that suitable geotechnical measures may be suggested for the overall safety of the project.

Buried channels can lead to severe damage in the storage dam projects if not identified and treated at an early stage of investigations. These buried/ paleo channels are mostly filled with riverine material and subsequently converted to old terrace deposits, which act as concealed pathways for the water conductor system.

Kundghat dam excavations

Kundghat dam (39.583 m high), an Earth and Rockfill structure across the River Bahaur, aims to impound a gross storage of 8.76 MCM at FRL (126.6 m) to harness the available water resources of the Bahaur River. The geological mapping of the dam site indicates that quartzite with subordinate schist is exposed on the right, while the left flank is occupied by the river-borne material, fluvial terrace, and slope wash without any rock outcrops.

Along the dam axis, a 351 m cut-off trench (COT) with the provision of a grout curtain has been designed as a principal measure for seepage control (Figure 2). Single line grout curtains were provided to initially try a widely spaced system of primary boles at a spacing of 6 m to 8 m, followed by secondary and tertiary holes at a progressively smaller spacing till the desired results of permeability value less than1 to 5 Lugeon (A Lugeon is defined as the water loss of 1litre/min/m of the drill hole under a pressure of 10 atmospheres maintained for 10 min in a drill hole of 46 mm to 76 mm diameter) are obtained.

The geological log of the COT reveals the presence of bedrock between 7 m and 14 m; however, the presence of a ‘paleo-channel between 110 m and 165 m was a geological surprise. The paleo river course was not picked up during geological mapping of the dam site area due to the cover of younger sediments (Fig.2).

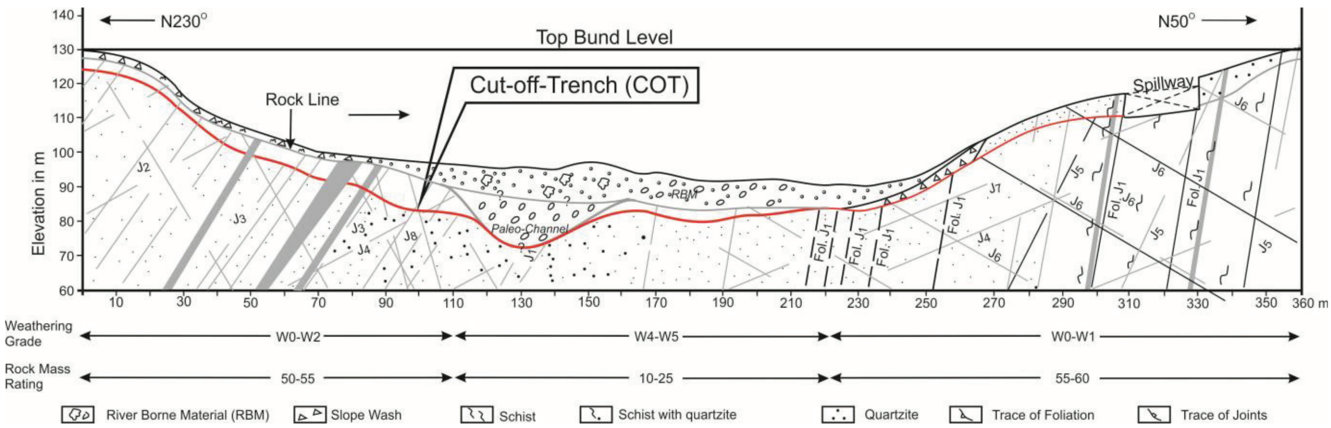

Figure 2, Geological section along the dam axis. The COT base (red line) shows the depth of the paleo-channel below the present bed level of the river.

Boulders, pebbles, and granules of varying sizes embedded in a sandy matrix comprised the paleo-channel material in about 55m section of COT posed a threat to the safety of the dam.

Table 1, Discontinuities observed in COT

Joint Set	Dip/ direction	Spacing (cm)	Continuity (m): Condition
Foliation / J1	40°/SV/20 0°/20°	3 - 15	>5; S, SU,
J2	73°/110°	3 - 10	1-3 m; R, P, with 2 mm to 1 cm opening
J3	61°/ W	3 - 5	1 - 3 m, S, P
J4	65°-70° /310°	5 - 20	1 - 5 m, S, SR, P
J5	75°/280°	6 - 20	0.5 - 2 m; S, R, P
J6	28° /15°	40	2m, S, P
J7	25°-46° /295°	10	1.6 m; S, P
J8	75° /SV/ 30°	6-10	1.5 m; R, P

SV-Sub-Vertical, S-Smooth, P-Planar, SU-Slightly Undulating, R-Rough, SR-Slightly Rough, SR-Smooth Rough

Paleo-channel materials were filled with unconsolidated to semi-consolidated sediments that reflect the environment of the ancient river system. The material types found include gravel and coarse to medium sand, the coarser materials with slower-moving water.

Geo-log of the Cut-off-Trench (COT)

Geological logging of the COT section reveals the presence of bedrock between 7 m and 14 m, and a paleo-channel in the valley portion. The COT section may be categorized into four segments, viz., Chainages (CH) 0-112 m; 112-210 m;210-240 m;240-248 m, depending on the conditions encountered. The details of geological conditions along the COT are as below: -

(1) From CH. 00 to CH. 112.5 m (Left flank): Moderately weathered micaceous quartzite with mica schist bands classified as class-III rock. The foliation of the rock trend N750W-S750E with dips 400-670 in a southwesterly direction along with five sets of joints

(2) From CH. 112.5 m to CH. 210 m (Paleo-channel/fossil valley in River section): The section exposes moderate to high weathered (W4-W5 weathering Grade) quartzite and mica schist below the paleo-channel (9 m to 13 m deep) or the fossil valley of the river. A zone of crushed quartzite has been mapped between CH. 110 m and CH. 140 m, possibly because of the fault along which the paleo-channel is passing.

(3) From CH. 210 m- to CH. 240m (River portion): Fresh and hard quartzite are intercepted in this section. The rocks are traversed by two sets of joints aligned askew to the dam axis.

(4) From CH. 240 m- to CH. 348 m (Right flank): Hard quartzite with weathered mica schist bands has been encountered.

Structural discontinuities in COT

Discontinuities, such as faults or joints in the dam foundations, can influence the dam's stability and performance. They allow water seepage or affect the transmission of loads. Detailed mapping of the dam trench area highlights seven sets of discontinuity surfaces and a well-developed foliation plane; the details of their orientation, dip amount, spacing, and continuities are shown in Table 1. The provision of curtain grouting to check the seepage below the foundation of COT is mandated owing to closely spaced foliation (Karmakar et al., 2016) having a cross-cutting relation with the axis of the dam, along with other sets of joints.

Permeability values in COT (pre-grout)

Permeability tests are an integral part of any grouting operation, and to decide the spacing between the Primary, Secondary or even Tertiary holes. The drill holes at center line of COT, done with 6m spacing as primary holes, and an empirical criterion

$$D = \frac{2}{3}H + 8$$

where *D* is depth of the hole kept for grout curtain permeability, and *H* is the height of the reservoir water decides the depth of the hole. The average permeability values in sections 0-112 m, 112-210 m, 210-240 m, and 240-348 m were computed in 3m stages with cyclic pressure indicate order of permeability values <5 lugeons, 22 lugeons (and in some sections up to 44 lugeons), <1 to 5 lugeon and <1-2 lugeon respectively. In the secondary drill holes with 3m spacing, these values are reduced to <1-3 lugeon; however, in section (110-165 m), the permeability values were found to be anomalous, and it was difficult to determine the permeability values.

Grouting technique as mitigation measures

Grouting, a vital geotechnical technique has been used to enhance dam safety by improving the foundation and preventing water seepage involving following stages.

Curtain grouting in COT

A provision of curtain grouting down to the depth up to 3/4H (H is the height of water retention at that point) has been provided as a measure of seepage control, in addition to an upstream impervious layer up to 10H (clay blanketing) has been provided and tagged to COT to increase the path of percolation as well as to reduce the anticipated seepage below the foundation (Sharma, 2018).

Along the dam axis, a 351 m cut-off trench (COT) with the provision of a grout curtain has been designed as a prime measure for seepage control. After filling the COT with the clay of variable depth, number of drill holes in a pattern of three rows (upstream row, downstream row, and center line) have been drilled and Primary (6 m spacing) and Secondary grouting (3 m spacing) grouting operations have been done in the COT area ensuring permeability (1-5 lugeon).

TAM Grouting in the paleo channel section

Drilled using the ODEX (Overburden Drilling Excentric) system, a specialized drilling method designed to simultaneously drill a borehole and install a temporary or permanent casing through unstable ground, such as loose soil, sand, gravel, and formations with cobbles and boulders. The system uses a down-the-hole (DTH) hammer along with casing up to the channel material, which is a collapsible stratum, then further drilling within the rock section has been performed.

After completion of drilling TAM (Tube a' Manchette) perforated PVC pipe with sleeves on perforations then inserted into the hole. Water cement and bentonite (2-5 % by weight of Cement) solution (Sheath Grout) were then filled around the TAM Pipe in the drill hole, and the casing was withdrawn. A hydraulically operated double packer with inter-packer distance of 0.60 m is then inserted and packers are hydraulically expanded to seal the section.

The paleo channel section in a depth range of 9-14 m (Figure 3), between CH 110m and 165 m (55 m), following an 'Off-pattern' grouting holes were drilled to consolidate the entire paleo-channel material, ensuring permeability values (1-5 lugeons). The method is repeated in drill holes done in the entire channel material in an off-pattern manner. The progression of techniques such as cut-off-trench, curtain grouting, blanketing, specific section TAM grouting and off-pattern grouting found to be most effective mitigation for potential leakage especially along paleo-channel encountered in the COT excavation.

Discussion and lessons learned

Epigenetic gorges (paleo-channels or fossil valleys) consist of channel-lag deposits, which are unconsolidated sediments having high permeability. Paleo-channels are parts of rivers representing channels abandoned by migrating rivers as they shifted their courses to carve new water courses. Despite remaining cut off from the active river flow, these features remain part of the flow regime of the active river system. These channels were formed due to river migration driven by neo-tectonic activity and climatic shifts or variability during the Holocene period. In the peninsular shield area, such features are generally concealed and difficult to locate, while in younger mountains such as the Himalayas, the epigenetic gorges are obvious to locate during the geological mapping of the dam sites and their environs. The presence of faults and lineaments in the basin influences both the river's path and the location of these paleo-channels. Paleo-channels are ancient, buried riverbeds formed due to past tectonic shifts or climate changes.

Dams, although mainly built on active rivers, interact with paleo-channels in many ways. The paleo-channels may pose significant challenges if encountered in the foundation of dams, reservoirs and have a connection with downstream, may endanger the stability of the superstructure. Understanding these channels is crucial for assessing the geological stability and potential risks of dam sites. The relevance lies in how paleo-channels may influence water flow patterns, sediment transport, and the overall stability of the dam foundation. Studies of these features ensure proper civil design and construction, minimizing the risk of foundation failures and enhancing the long-term safety of the dam. In the context of dam construction and reservoir management, epigenetic gorges are crucial because dams built near or across such gorges must account for the potential for differential erosion or seepage in reservoirs, and epigenetic gorges help model how water might bypass or undermine dam structures during extreme events.

Figure 3, Course of the paleo-channel intercepted in excavations of the Cut-off-Trench (Source: GoogleEarth).

Delineation of paleo-channel course in the Kundghat dam foundation was a unique case of such ancient channel within plateau of Chhotanagpur Gneissic Complex (CGC), mostly forested, where routine geological mapping could not locate the channel possibly due to slope wash cover (Figure 3). It is therefore imperative that treatment of paleo-channels in dam foundations should involve a comprehensive geological and engineering approach that includes

(i) site investigations (geological, geophysical, and drilling explorations)

(ii) foundation design to adjust the parameters of variations in soil and rock properties

(iii) grouting to fill voids to improve stability and permeability of channel material

(iv) cut-off walls to intercept potential seepage path and (v)engineering barriers such as clay or concrete cut-offs,

The successions of grouting techniques were found useful in addressing foundation leakage while managing the risks to the dam. Grouting, a geotechnical process, also helps to improve soil or rock properties by injecting a fluid material (grout) into a formation, which then hardens. The effectiveness of grouting depends heavily on understanding the ground geological conditions and selecting the right techniques for structural integrity and safety of the dams.

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Author contributions

Vinod wrote the manuscript, prepared the figures, and revised the article. He is the sole author of this article.

Data availability

No datasets were generated or analyzed during this study.

Declarations

The author declare that he has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this article.

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