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Rainfall induced instability of mechanically stabilized earth embankments

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Abstract. A 10.4-m high highway embankment retained behind mechanically stabilized earth (MSE) walls is under construction in the northeastern part of the Indian state of Bihar. The structure is constructed with compacted, micaceous, grey, silty sand, reinforced with polyester (PET) geogrids, and faced with reinforced cement concrete fascia panels. The connections between the fascia panels and the geogrids failed on several occasions during the monsoon seasons of 2007 and 2008 following episodes of heavy rainfall, when the embankment was still under construction. However, during these incidents the MSE embankment itself remained by and large stable and the collateral damages were minimal. The observational data during these incidents presented an opportunity to develop and calibrate a simple procedure for estimating rainfall induced pore water pressure development within MSE embankments constructed with backfill materials that do not allow unimpeded seepage. A simple analytical finite element model was developed for the purpose. The modeling results were found to agree with the observational and meteorological records from the site. These results also indicated that the threshold rainwater infiltration flux needed for the development of pore water pressure within an MSE embankment is a monotonically increasing function of the hydraulic conductivity of backfill. Specifically for the MSE embankment upon which this study is based, the analytical results indicated that the instabilities could have been avoided by having in place a chimney drain immediately behind the fascia panels.

Keywords: mechanically stabilized earth (MSE) wall; embankment; rainfall; unsaturated; seepage; stability; drainage.

1. Introduction

A 10.4 m high mechanically stabilized earth (MSE) embankment is under construction for a highway widening project in the northwestern part of the Indian state of Bihar (Fig. 1). The construction work began in June 2006. The structure is being constructed with compacted, locally available, micaceous, grey silty sand with a fines-content of up to 30%. The backfill is reinforced with PET geogrids with an ultimate tensile strength ranging from 60 kN/m (within the top 1.2 m of the embankment) to 150 kN/m (at depths of more than 6 m from the embankment top). The geogrids are manufactured from high molecular weight and high tenacity polyester yarns by Techfab

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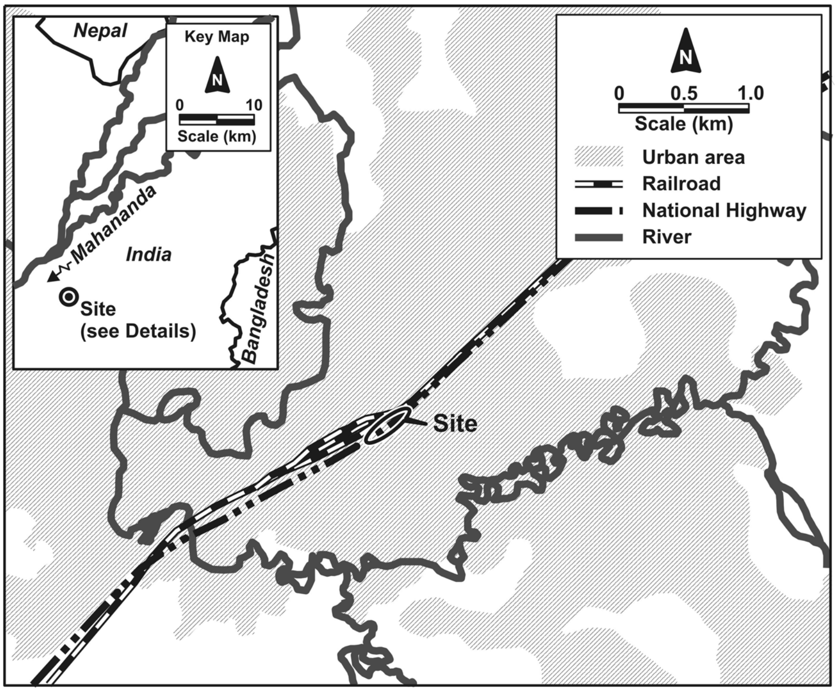

Fig. 1 Site location

India. The vertical spacing of the geogrids was 750 mm. Reinforced concrete fascia panels, 1580-mm in height, 1480-mm in width and 180-mm in thickness equipped with hooks on their inside faces for connecting the geogrids were used to prevent erosion. The geogrids were connected to the fascia panels using mortar-filled PVC pipes. There batter of the finished outside face of the MSE wall is 1 (horizontal) to 20 (vertical). Geode PPEXT 140 (manufactured by Edilfloor, Italy) strips of 200-mm (for horizontal strips) to 400-mm (for vertical strips) width were pasted behind the fascia panels at all fascia panel joints to prevent washing out of backfill soil through the inter panel gaps. No chimney drain was used behind the fascia panels. Fig. 2 shows the appearance of finished MSE wall and the connection details between geogrids and fascia panels.

The MSE embankments have suffered six major episodes of instabilities involving bulging, separation and loss of fascia panels due to the failure of connections between fascia panels and geogrids. Although fascia panel instability is possibly the most prevalent distress mechanisms for MSE walls (Koerner and Soong 2001, Leschinsky 2008a), it received only a scant attention in literature. These writers, for instance, are aware of only a few publications dealing with MSE embankment fascia panel loss following episodes of heavy rainwater infiltration (e.g. Koerner and Soong 2001, Colin 2001, Leschinsky 2008a).

Over and above the general difficulty to report a case history on non performance, the apparent lack of attention with regards to this particular failure mode appears to be due to: (a) the failure mode does not usually affect the overall functionality of the MSE embankment and can be repaired without causing disruption to services, and (b) a simple procedure is not available for quantifying its causes.

Provision of an engineered chimney drains immediately behind the fascia panels, often considered sufficient to preclude such a failure (Koerner 2005), may not always be adequate (Leschinsky

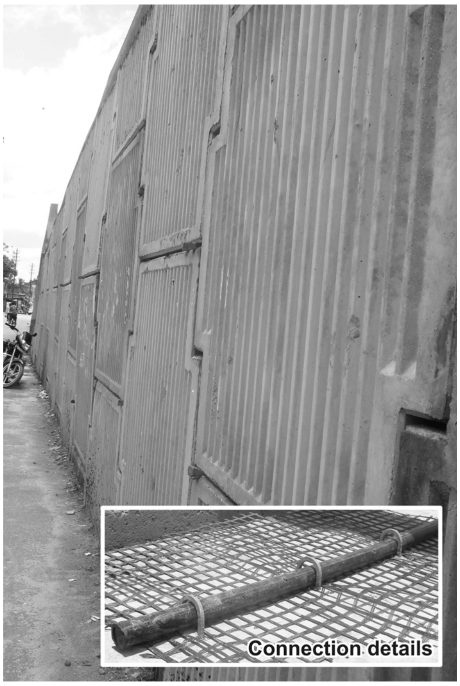

Fig. 2 MSE wall: Appearance and connection details between fascia panels and geogrids

2008b). An additional provision for surface drainage to minimize rainwater infiltration is therefore usually recommended particularly during the construction phase to avoid rainfall induced pore water pressure development. These measures lead to an increase in the construction cost and cannot be easily implemented at sites exposed to sudden and very intense rainfall. Unfortunately, there is no simple guidance on the nature of backfill or infiltration rates for which such remedial measures can be avoided.

These writers are unaware of any prior analytical investigation on rainfall induced pore water pressure development approximately accounting for the strong dependence of hydraulic conductivity on the degree of saturation of the soils except one reported by Yoo and Jung (2006). This study involved back analysis of a rainfall induced deep seated instability of an MSE embankment using a loosely-coupled, finite element model for seepage as well as deformation analysis. Since developing a similarly elaborate analytical model and constraining it adequately with regards to material and meteorological inputs is often not feasible in a routine project a simpler uncoupled approach is expected to be more useful. For the problem at hand only seepage analysis was undertaken. No deformation modeling was considered necessary because of the absence of an indication of internal or deep-seated instabilities.

While setting up the seepage model is not particularly involved as illustrated later, a rigorous and site-specific assessment of rainfall induced pore water pressure development is only possible if the backfill is characterized for its hydraulic conductivity, itself a function of volumetric water content, and the soil moisture characteristic curve, and the mechanical strength of the geogrid to fascia panel connection are available. Typically even these parameters are not available to the designer.

The objectives of this article are to develop (a) a simple analytical model for assessing the likelihood of rainfall induced pore water pressure development and calibrating the procedure based on the observations obtained during the instabilities and (b) a design aid which will allow a preliminary estimate of rainfall induced pore water pressure development without the need for a non-routine material characterization. We set out by describing the site setting and the development details. The analytical exercise and the results presented subsequently are compared against observations for validating the results. Finally, the suggested reconstruction measures for the affected stretch of the highway project are presented.

2. Geologic setting

The affected stretch of the MSE embankment is located within the Mahananda River basin in the northeastern corner of Indian state of Bihar. The area is underlain by alluviums of thickness as high as 1 km or more. The terrain is flat and transected by a number of meandering drainage channels. The subsurface soils are mainly comprised of loose to medium dense, gravel bearing, micaceous sand. The average standard penetration test (SPT) blow count was 7 within the 5 m from ground surface and about 15 between 5 m and 15 m depths. Considering the SPT setups used in India typically delivers about 45% of the theoretical energy, the SPT blow counts measured within the foundation soils are representative of loose to medium dense deposits. Groundwater table occurs near ground surface over a large part of the year. Such subsurface conditions are usually deemed to have bearing capacities large enough to provide static support to loads imposed by a high MSE embankment.

3. The development

The embankment will function as the north and south approaches of a national highway to a road overpass. Running parallel to the embankment along its western margin is the existing national highway that is being improved. Immediately to the west of the current alignment is a major railway facility that connects northeastern India with the rest of the country. Along the eastern margin of the embankment under construction is a service road. Once constructed, the road overpass supported on the MSE embankments will carry the through traffic of the national highway and segregate it from local traffic of the urban center within which the facility is being constructed. The

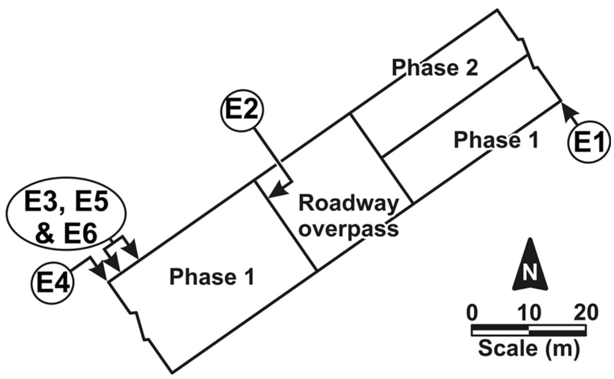

Fig. 3 Wall layout

southern part of the embankment will be completed in one phase (Fig. 3). The northern part will be constructed in two phases. The eastern half of the MSE embankment will be constructed first. Subsequently, the embankment will be extended westward to cover the present-day alignment of the national highway.

4. Events

There have been six major incidents of fascia panel instability: June 8, 2007; August 28, 2007; September 15, 2007; May 15, 2008; June 13, 2008 and June 17, 2008. The approximate locations of these incidents, referred to as E1, E2, E3, E4, E5 and E6, respectively, are shown in Fig. 3. The failures were caused by separation of fascia panels because of shear-related deformation or breakage of the polymer pipes used to connect the fascia panels to the geogrids as shown in Fig. 4. It needs to be mentioned here that the incident illustrated in Fig. 4 was initiated by separation of only nine fascia panels. The surrounding panels showing signs of distress were manually removed after the separation of nine fascia panels to ensure public safety. On certain occasions, e.g., E1, backfill washed out through the gaps in between fascia panels in spite of the presence of geotextile barrier to preclude such a soil loss. At the locations of the failures, no instability was noticed apart from the separation of fascia panels. Minor distress also developed at a few locations on the MSE embankment outer face involving bulging out of fascia panels and development of negative batter.

The fascia panel separation appears to begin with progressive bulging of inter panel joints near the top of the embankment. These observations indicate that the failures and the distress were caused by increase in the degree of saturation of the backfill material near the top of the MSE embankment because of rainwater infiltration and the consequent increase in pore water pressure. Similar pattern of infiltration-related pore water pressure development within partially saturated soils is reported by others (e.g. Lambe 1948).

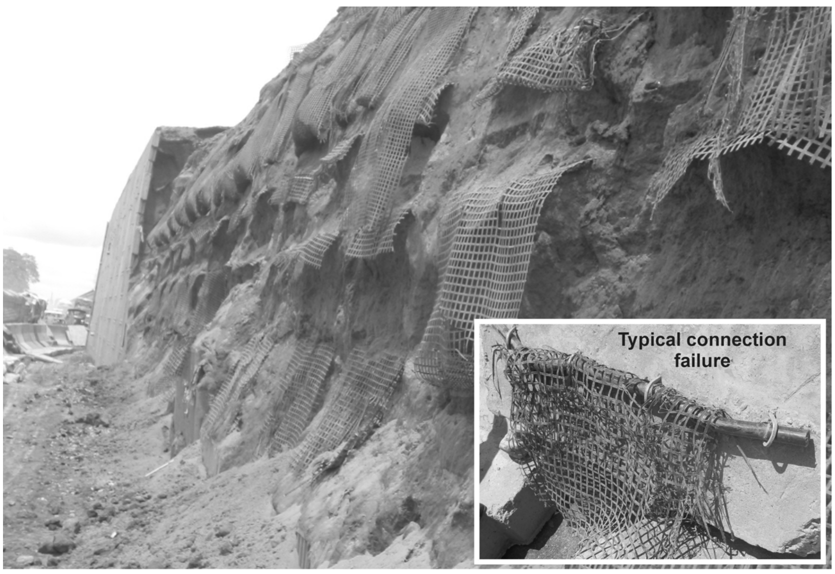

Fig. 4 Location of fascia panel failures of June 28, 2008 (photograph looking north)

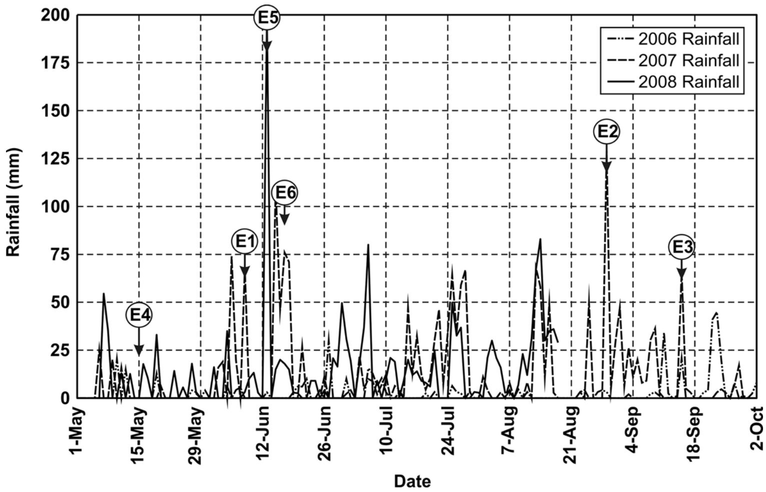

Fig. 5 Daily rainfall intensity and fascia panel instability

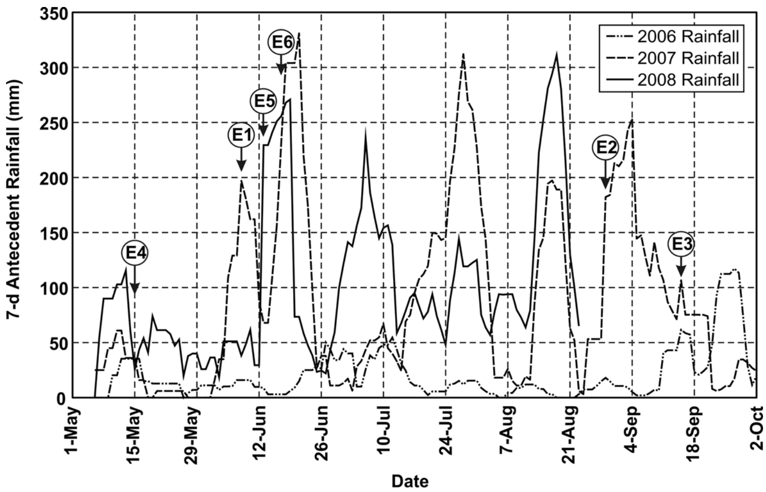

Fig. 6 Seven day antecedent rainfall and fascia panel instability

Review of rainfall data and the timing of failures indicate that incidents E1, E2, E3 and E5 closely followed episodes of heavy rainfall (Fig. 5). The remaining two incidents, E4 and E6 were preceded by two episodes of high 7-day antecedent rainfall (Fig. 6). Data up to August 18, 2008 from a local weather station were used to prepare these figures.

Thus, the first category of failures (E1, E2, E3 and E5) appears to have been caused primarily because of development of rainwater infiltration related transient pore water pressure, and the second category (E4 and E6) appears to have been due to the development of cavities underneath the geogrids and/or behind the fascia panels. It also appears that E6 is a direct aftermath of E5. Incident E3 may similarly have lead to the development of increased erosion rate in the vicinity of its location, which appears to be the possible cause of incident E4.

These writers were not involved with the original design and construction of the MSE embankment. They were engaged to study the possible causes of the distress and suggest remedial measures for reconstruction.

5. Stability assessment

5.1 Internal stability

The internal stability of the pre failure configuration of the MSE embankment reinforced with the geogrid was assessed for breaking and pullout of geogrid. The estimated factor of safety against the breaking of geogrid was 1.8 and that against pullout was 3.2 compared to a target factor of safety of 1.5 against internal stability. These results indicate an adequate margin against internal instability as was observed during post failure inspection. No observational evidence indicating internal instability was found during post failure investigation.

5.2 External Stability

The external stability of the pre failure configuration of the MSE embankment was assessed against sliding, overturning, and bearing capacity failure. The factors of safety against sliding and overturning were estimated to be 1.9 and 4.1, respectively. The factor of safety against bearing capacity failure was estimated at 1.8. The line of action of the resultant force was within the middle third of the MSE wall base. Consequently no tension is expected to develop at the base of the wall. In comparison, document IRC: 75-1979 (Indian Roads Congress 1979), which governs the design of highway embankments in India, calls for a long term factor of safety of 1.25. Therefore, results of stability assessments indicate an adequate margin against external instability as was observed during post failure inspection. The impact of infiltration related pore water pressure development was not examined in the original design.

6. Seepage analysis

A series of seepage analyses were completed for (a) estimating the pore water pressure development due to rainwater infiltration, (b) assessing whether chimney drains behind fascia panels could be used to prevent such pore water pressure development and (c) assessing the critical flux above which pore water pressures are expected to develop as a function of the hydraulic conductivity of the backfill. The details of the model and the results are discussed below.

6.1 Numerical model

In these analyses SV Flux (part of SV Office version 1.62.25) finite element software package (Soil Vision System 2008) was used. The package solves the following partial differential equation for a plane groundwater seepage problem through saturated or unsaturated soils similar to that being examined in this article:

$$\frac{\partial}{\partial x}\left[k(\theta)\frac{\partial h}{\partial x}\right]+\frac{\partial}{\partial y}\left[k(\theta)\frac{\partial h}{\partial y}\right]=-\gamma_w m\frac{\partial h}{\partial t} \tag{1}$$

where r and y are the radial and vertical directions, respectively, $k(\theta)$ is the radial (horizontal) hydraulic conductivity (which depends on volumetric water content, θ), h is the hydraulic head, m

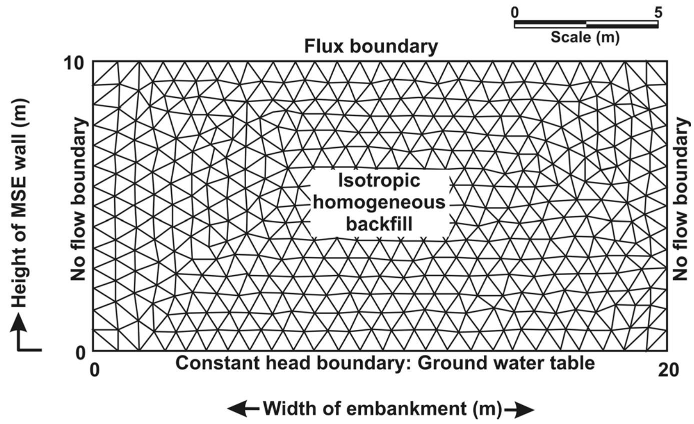

Fig. 7 Finite element seepage model

is the derivative of the soil water characteristic curve with respect to the matric suction, γ_w is the unit weight of water, and t is time. Since the soil water characteristic curve represents the characteristic volumetric water content as a function of matric suction, the procedure considers the hydraulic conductivity to vary with matric suction. The interaction between vapor and liquid phase of groundwater was neglected in this analysis.

A cross section representative of the highest configuration of the MSE embankment was modeled numerically using three-node triangular elements (Fig. 7). The backfill material was assumed to be homogeneous and isotropic. For the backfill soil the soil water characteristic curve shown in Fig. 8 and hydraulic conductivity function shown in Fig. 9 were used in the analyses. The volumetric water content for the embankment material with respect to the suction was estimated using the soil water characteristics curves following Fredlund *et al.* (1997). The hydraulic conductivity function was estimated according to the modified Campbell method (Fredlund 1996, 2004) as applicable for silty sand backfill.

It needs to be highlighted that the numerical model used for assessing rainfall induced pore water pressure rise is expected to provide conservative estimated because the following factors were neglected: (a) out of plane seepage across the fascia panels (in spite of the permeable nature of the

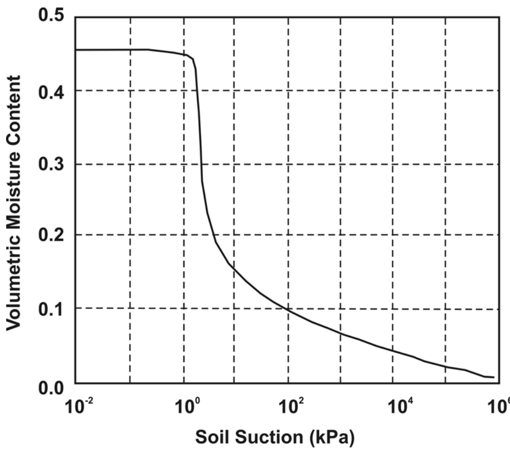

Fig. 8 Soil water characteristic curve

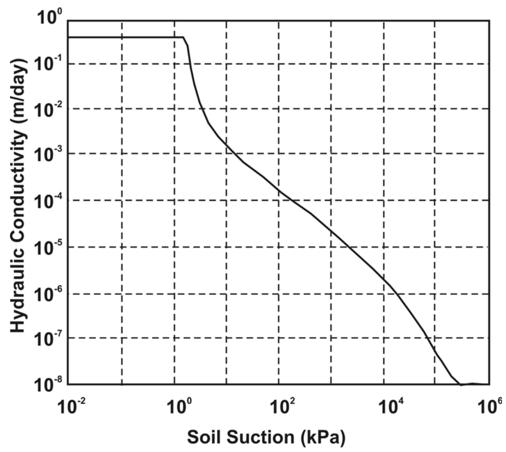

Fig. 9 Hydraulic conductivity function

joint between individual fascia panels), (b) in-plane drainage capacity of the geogrids, and (c) longitudinal runoff along the MSE embankment. These simplifying assumptions allowed setting up a numerical model that is simple and user-friendly yet capable of capturing the groundwater seepage through unsaturated soils.

6.2 Results

The pore water pressure response following 24-hour of simulated infiltration of a constant flux through the top surface is presented in Fig. 10. Results indicate that rainfall-related pore water pressure build up begins as the rainwater infiltration flux exceeds 0.4 m/d, which is equivalent to daily rainfall intensity of about 21 mm for the MSE wall configuration being studied, for the silty sand backfill used in constructing the MSE wall. From Fig. 10 it appears that the pore water pressure build up becomes significant when the infiltration flux exceeds 0.6 m/day, *i.e.*, daily rainfall intensity of about 32 mm. In comparison, the rainfall intensity and fascia panel instability data presented in Fig. 5 indicate that the threshold daily rainfall intensity for the development of fascia panel instability is about 50 mm. The difference between the observation and the results of seepage analyses is explained by the conservatism in the numerical model used in this study and the fact that the strength of the connections between geogrids and the fascia panels was neglected while making the assessments.

Based on the results of seepage analyses, no pore water pressure build up is expected when a 300-mm thick chimney drain is used immediately behind the fascia panels characterized with a hydraulic conductivity of 1000 times that of the backfill material for an infiltration flux of up to 55 m/day.

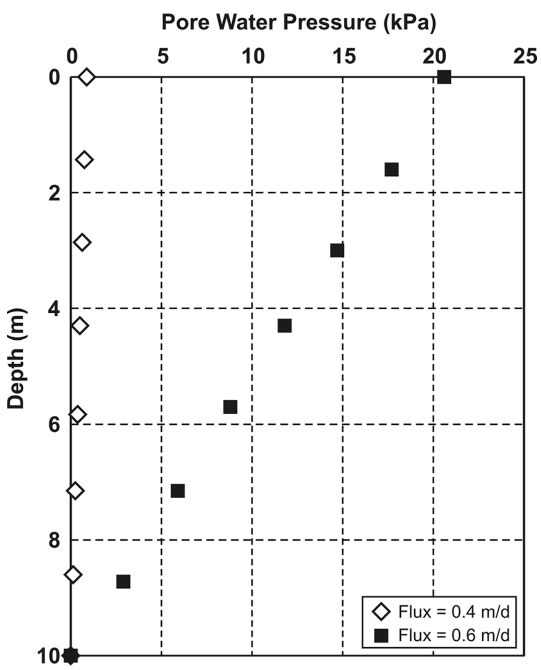

Fig. 10 Pore water pressure development due to rainwater infiltration

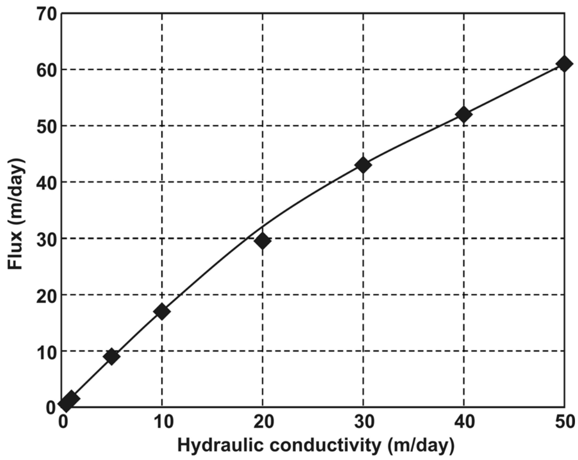

Fig. 11 Flux required for pore water pressure development

Fig. 11 presents the critical infiltration flux above which the infiltration-induced pore water pressure begins to build up as a function of the saturated hydraulic conductivity of the backfill material. The hydraulic conductivity function presented in Fig. 9 was arithmetically scaled up for developing the hydraulic conductivity functions used in these computations. As for Fig. 10, these results represent the pore water pressure response of the backfill following 24-hour of simulated infiltration of a constant flux through its top surface. The results presented in Fig. 11 represent infiltration flux of up to 60 m/d. Such an infiltration flux is approximately four times greater than the maximum daily rainfall observed at the site (800 mm/d) over the last five years. The MSE wall designer needs to make a decision regarding the design infiltration flux with duly considering the severest expected rainfall intensity and the likelihood of piping and clogging, and the consequent reduction in the flow capacity through the backfill.

Although Figs. 10 and 11 could be viewed as a conservative threshold needed for the development of rainfall induced pore water pressures within an MSE embankment, the charts are applicable for predominantly downward seepage regime. Thus, these charts should not to be used for assessing the response of a hillside MSE embankments hosting horizontal or nearly horizontal seepage.

7. Reconstruction measures

Observational evidence and analytical results presented in this article indicate that the MSE wall fascia panel instability was because of rainwater infiltration and the consequent increases in pore water pressure. The connections between the fascia panels and geogrids were not designed for such elevated magnitudes of pore water pressure. The problem could thus have been avoided if a chimney drain was installed behind the fascia panels and the rainwater intercepted at the surface of the embankment could be carried away without allowing infiltration.

Two alternative designs - one based on geotextile and one on select granular material - were developed. Both these schemes are capable of carrying a daily discharge of 1.35 m^3/day (equivalent daily rainfall intensity of 68 mm) with a factor of safety of 3. They meet the filter criteria for the backfill material under use. The reconstruction is proceeding with a chimney drains behind the fascia panels, 300-mm in thickness, constructed with select granular material. The connections between the fascia panels and the geogrids were also strengthened to mobilize the long term design strength of the geogrids before failure for added safety.

8. Conclusions

Separation of fascia panels due to infiltration related pore water pressure development is one of the most prevalent failure mechanisms of MSE walls. Although, it is well known that such instabilities could be avoided by draining the infiltrating rainwater via chimney drains or by preventing infiltration employing a network of surface drains, guidance on the flux rates that would necessitate such measures is non existent.

Six incident of similar nature recently affected a short stretch of highway embankment currently under construction in the northeastern part of the Indian state of Bihar presented an opportunity to develop a design aid for approximate assessment of rainfall induced pore water pressure rise within an MSE embankment. During these incidents fascia panels separated from the geogrid-reinforced backfill because of failure of non-engineered connections between geogrids and fascia panels. Precipitation data from a local weather station clearly shows that the incidents were in all cases preceded by heavy rainfall. It was thus inferred that the incidents were due to pore water pressure increase because of rainwater infiltration into the backfill.

The threshold infiltration flux above which pore water pressure is likely to build up within MSE wall backfill has been identified as a function of saturated hydraulic conductivity for general guidance to the designers. The tool could be used as a conservative assessment of the likelihood of rainfall induced pore water pressure rise within an MSE embankment hosting predominantly downward seepage.

The suggested reconstruction measures for the affected MSE embankment included a chimney drain based on coarse granular soils on the inside face of the fascia panels. The efficacy of such a drain could be established from seepage analyses. Additionally, the connection between the geogrids and fascia panels were suggested to be strengthened to ensure the mobilization of the long term design strength of the geogrids before fascia panel separation becomes possible. Reconstruction has been taken up adhering to these recommendations at the time of preparation of this manuscript.

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