Embankment Dam Design With Dispersive Soil: Solutions And Challenges

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Abstract

An embankment dam has been designed by using dispersive soil in East Africa after performing the required tests for dispersivity of the materials. Internal erosion through cracks or other openings in the embankment is the most concern of using the dispersive soils. The foundation of dam and borrow areas consist of dispersive soil and the effective measures has been considered in the design to safely deal with dispersivity according to recommendation of the codes and design guidelines. The selected solution was the combination of chimney filter, filter drain, and selective placement of materials in the dambody as the effective solution considering the specification of the project. The local instability in the contact zones was the concerns of designers and bilinear parameters has been considered in the stability analysis as the base case. This was due to the dispersive material and drain filter feature that determined according to nonlinear static and dynamic analysis of the dambody. This paper presents the measures and precautions that were taken into account in dealing with dispersive soil in order to ensure the safety of project.

1. Introduction

Dispersive, erodible, and slaking soils are prevalent over wide areas of the world. Dispersive clay soils collapse or disperse to form dissolved slurry when in contact with water. Using the material increases the risk of erosion in the dams during operation if precaution is not taken properly. The erosion usually occur by cracking resulting from different settlements caused by poor compaction in the vicinity of conduits. The failure is also common when the filling of the reservoir is rapid, however, some embankments have also failed after surviving an initial filling when later subjected to a higher water head than the initial filling.

The recommendation of the codes and references is to avoid using the dispersive soil if possible, however, there are some solution for dealing with dispersive where it is inevitable. Dams and other hydraulic structures can safely be built with dispersive clay materials if certain precautions are taken. The references state that "*The measures include, but are not limited to, proper moisture and density control, use of filters and filter drains, select placement of materials, use of sand-gravel blankets or lime-modified soil on slopes, and chemical treatment of dispersive clays*" (Icold Bulletin 1990, DPIW 2009).

Many dams have been built using the dispersive material in the world. In Australia, Eildon, Cairn Curran, Ross river, and Mole River dams (SMEC, 2020, Lesleighter, et al. 2004, Swindon, et al. 2003, Fell, et al., 2015) were upgraded using the dispersive soil. The filter solution has been used as an effective method to deal with internal scoring. In Eildon dam, as part of the embankment raising works, the issues with piping were addressed by the installation of properly designed filters to the top of the dam. The use of sand filters was adopted over other options such as lime stabilisation. In Cairn Curran dam, the existing embankment materials were highly dispersive and very fine. To figure out the internal erosion, a two stage fine filter was designed with a very fine filter, produced from rock crusher dust, used in locations where the likelihood of piping was highest. In Ross river dams, the existing embankment materials were highly dispersive with very prevalent “tunnel” erosion of the outer shoulder. Risk of piping through the crest of the dam was considered an unacceptable risk and the existing filters did not meet modern design standards. Therefore, filters were retrofitted in the critical area along the length of the embankment. In Mole River dam, the downstream filter arrangement comprises both a fine filter and coarse filter. The downstream filters were designed to satisfy critical filter criteria as detailed in Fell et al (2015). In view of the potential dispersive nature of the core material, the maximum d15 size of the fine filter has been set at 0.5mm rather than 0.7mm as adopted for non-dispersive core material, based on the recommendations given in Fell et al (2015). However, for design purposes it was considered that no-erosion filter tests would be undertaken to confirm the acceptability of the dispersive core/fine filter arrangement, and hence the required fine filter grading.

Richards, et al. (2007) presented a review of published literature on soil piping phenomena. They indicated that the recent work on piping highlights the limitations of the occurrence of piping and the role that design and construction may play in a large percentage of piping failures. They also showed the standardized laboratory procedures are available to assess piping potential in cohesive materials, but no such methods exist for noncohesive soils, however; methods are available for evaluation of self-filtration potential. Paige-Green (2008) has summarized the fundamental differences in the material, discussed current tests methods to differentiate between them and reviewed the techniques for refining them as construction material. He has concluded that the state-of-the-art has progressed little since the problem of using dispersive was discussed at the 1985 problem soils conference. NAGY, at al. (2015) presented the background of the dispersive soils, and the mechanism of failure, the tunnel erosion. They concluded that the identification of dispersive clays is a multi-faceted assessment process, where none of the methods of the identification ensures 100% certainty. They have indicated that the pinhole test is a well-used method, but for the certainty, it should be confirmed by other techniques, such as the geoelectric measurements, or the standard void ratio. McCook D. k. (2016) has presented the required samples and tests for identifying dispersive materials. Minimum 20-30 samples has been recommended for even small embankment projects and Crump test has been introduced as the best method of establishing whether dispersive clays are likely present. TOSUN (2006) briefly presented tests to determine the dispersibility properties of soils and summarizes the procedures to be adopted for embankment dams with dispersive soils in Turkey. He outlined the geotechnical investigation to determine its failure mechanism and also introduces the construction measures taken into account for Tınaztepe dam in Turkey, which failed due to internal erosion of dispersive soil along the conduit. Guan (2018) described the design and construction challenges of the Marlborough dam in New Zealand by the use of the dispersive loess material, and the innovative approach to processing of complying filter material that were used in the development of a cost constrained dam, in an area of high seismicity. The key risks to dam safety were assessed as the local seismicity and the potential for internal erosion of the dispersive loess material used in the dam shoulders. Singh, et al. (2018) tried to analyze the basic characteristics, problems and stabilization with suitable additives. They concluded that the Double Hydrometer test and Chemical analysis of pore water extract test are more conservative in showing the dispersion of soil. They indicated that the pinhole test is more reliable as it simulates field conditions and the crumb test gives a good indication of the soil for potential tendency to erosion. They also showed that the strength of dispersive soil increases with increase in lime, alum and gypsum content up to certain limit.

This paper presents concerns and challenges of embankment dam design with length of 15 km at the saddles of a big reservoir in east Africa with a total capacity of 30 BCM at normal water level. The main and saddle dams and hydropower plant are under construction at the moment and the saddle dams are deemed as high hazard structure since they hold 40% of the reservoir capacity in the minimum foundation level.

2. Dam Site And Borrow Area Characteristics

There is a limited availability to the convenient material for building the saddle dams located in the right ridge of reservoir with huge capacity of 30 Billion Cubic Meter in east Africa. The ridge level will be risen by the three embankment saddle dams with a length of approximately 15 km. Notwithstanding the maximum height of the saddle dam is 20 m in the lowest level of the valley, it is an important structure due to holding maximum 38% of the reservoir capacity.

Field tests have been used as helpful method in preliminary evaluation of dispersive or nondispersive character of the soil. The reliability of the field test is limited and laboratory tests have been used to further studies. Four special laboratory tests namely Pin hole, SCS double hydrometer, Crumb, and Chemical analysis of pore water have been used for assessing dispersive characteristics. The results show that none of the four tests truly identity the dispersive nature and there is a wide discrepancy between the outcomes of each of the four tests.

Most of the available borrow material that identified around the project, has dispersive characteristics based on the field and lab tests results. In the preliminary stages of studies, only double hydrometer tests were performed and almost all of double hydrometer tests have shown dispersivity of the borrow material. The crumb tests were also performed on some samples in this stage. These tests have also confirmed soil dispersivity. Numerous double hydrometer tests were performed in the detail design stage and almost all the results were in the dispersive category. In detail design, complementary pinhole tests were also performed on a large number of samples. According to these tests, only 2 samples out of 40 were evaluated dispersive completely. Given that crumb tests have confirmed soil dispersivity, the material was deemed dispersive and special precaution was considered in the design. Some of the tests results are presented in Tables 1 and 2.

Table 1. Some of dispersivity tests results on borrow material

Sample	Dispersive test				Final judgement
	Crumb test method		Double hydrometer method		
	Grade	Judgement	Percent dispersion	Judgement	
1	1	Non	94	Dispersive	
2	1	Non	68	Dispersive	Dispersive
3	2	Intermediate	88	Dispersive	Dispersive
4	3	Dispersive	74	Dispersive	Dispersive
5	2	Intermediate	47	Intermediate	Intermediate
6	2	Intermediate	70	Dispersive	Dispersive
7	2	Intermediate	83	Dispersive	Dispersive
8	1	Non	60	Dispersive	Dispersive
9	4	Highly	67	Dispersive	Dispersive
10	3	Dispersive	50	Dispersive	Dispersive
11	2	Intermediate	100	Dispersive	Dispersive
12	2	Intermediate	44	Intermediate	Intermediate
13	3	Strongly	-	-	Dispersive
14	3	Strongly	-	-	Dispersive
15	2	intermediate	-	-	intermediate
16	2	intermediate	-	-	intermediate
17	0	Non	-	-	Non
18	2	intermediate	-	-	intermediate
19	2	intermediate	-	-	intermediate
20	4	Completely	-	-	Dispersive
21	0	Non	-	-	Non
22	3	Strongly	-	-	Dispersive
23	3	Strongly	-	-	Dispersive
24	4	Completely	-	-	Dispersive

Table 2. Some of Pinhole tests results on borrow material

Sample	Pinhole test	Remark
1	ND4	Intermediate
2	ND4	Intermediate
3	ND3	Intermediate
4	ND2	Non disperse
5	D2	Disperse
6	ND1	Intermediate
7	ND1	Intermediate
8	ND4	Intermediate
9	D1	Disperse
10	ND3	Intermediate
11	ND3	Intermediate
12	ND3	Intermediate
13	ND3	Intermediate
14	ND4	Intermediate
15	ND4	Intermediate
16	ND3	Intermediate
17	ND3	Intermediate
18	ND1	Non disperse

Statistical factors of Soil index properties of one selected zone in borrow area are summarized in Table 3 and gradation curves of the material is shown in Figure 1.

Table 3. Soil index properties of one of selected part of the borrow area

Statistical factors	Particle size distribution					Densities	Consistency		
	0.002 mm	.0002 to 0.063 mm	0.063 to 2.0 mm	2.0 to 63 mm	Fine content	Density of solids	Liquid Limit	Plastic Limit	Plasticity Index
	Clay	Silt	Sand	Gravel		ρs	LL	PL	Ip
	%	%	%	%	%	Mg/m^3	%	%	%
Min	0	3	1	0	3	2.38	22	9	11
Max	51	97	92.3	56	99	2.74	52	24	37
Average	14.76	31.27	53.28	2.03	44.71	2.6	36.05	14.01	24.09
STDEV	11.97	20.67	25.29	8.07	25.99	0.07	7.62	3.23	6.04

3. Typical Solutions In Deal With Dispersive Soil

The most common cause of the failure of earthen embankments constructed of dispersive clay is internal erosion through cracks. Cracking can initiate by:

- Hydraulic fracturing, induced by drilling, grouting, or other foundation preparation.
- Desiccation cracks, usually transverse to the structure, in arid areas.
- Interruptions in placement of the fill during construction, which can allow the soil to dry out.
- Differential settlement around dam conduits and other appurtenances that were improperly compacted.
- Discontinuities at the embankment or foundation interface that can form cracks, particularly if the bedrock has not had proper foundation treatment prior to placement of the fill.
- Open fractures or bedding planes in a bedrock foundation, whether they are open or partially filled with soil that can act as the point of initiation for cracking.

When dispersive clays are detected in a site investigation, several defensive measures can be incorporated into the design as follows (USAD 1991):

A. Chimney Filter

The most effective design measure for preventing internal erosion of earth fills that impound water is a sand chimney filter. A sand chimney filter is usually designed as a vertical zone in an embankment and place near centerline of the dam for central core design. It is generally about 2 to 3 feet wide and extends below any excavation and upward to the elevation of the planned maximum water

B. Selective Materials Placement

Occasionally, materials in proposed borrow areas may be clearly identified as being completely dispersive or nondispersive. Dispersive clay is generally placed in the interior of earth fills upstream of the core where the zone is not relied on as a barrier to seepage or internal erosion.

If nondispersive or less dispersive soils can be located, they can be used to blanket the surface of an embankment. Sands or gravels with nondispersive fines may also be used for this purpose. This blanket protects any underlying dispersive clay from developing drying cracks and thereby reduces jugging.

C. Chemical Amendments

A variety of chemical amendments have been used to alter the characteristics of dispersive clay and make them suitable for use in blanketing the external slopes of embankments. They are also used in impermeable zones within the embankment. The chemicals used include hydrated lime, alum, fly ash, gypsum, agricultural lime, magnesium chloride, and mixtures of hydrated lime with agricultural lime (Sayehvand S., Dehghani M., 2014).

4. The Design Challenges

Different measures has been considered in the different stage of studies to decrease the internal erosion risk of the dispersive material in the dambody and foundation. In the tender design stage, asphalt core earthfill dam was the selected alternative, however; due to limited access to the asphalt, the design changed to embankment Dam with geomembrane in upstream face in the basic design. There were two major concerns about this option including surface protection against waves and concrete slabs stability under the geomembrane layer. The height of the dam as the result of wave height can increase by decreasing roughness of upstream face layer and make the project expensive. The modified alternative was to use geomembrane in the central part of embankment as an impermeable core, however; this alternative was also rejected due to employer requirement for using local material and unavailability of the geomembrane in the region.

A. Final Basic Design

The chimney filter was considered as an effective measure for internal erosion control in the basic design stage. In addition to chimney filter, a 2% Lime treated clay layer with thickness of 112cm was placed in upstream face beneath the riprap layer. The cross section of embankment in the final basic design as shown in Figure 2, includes the chimney filter in downstream axis of the dam, the lime treated layer beneath the riprap in upstream, grout curtain in the upstream toe of the dam, and drain trench in downstream toe.

Chimney filter collects seepage from core and allows it to flow to horizontal filter. Chimney/vertical filter being a pervious barrier intercepts all potential transverse cracks through body of the dam and prevents piping. This is useful in case of homogeneous section where the dam is made of dispersive silty and clayey soil. Chimney filter is a costly preposition and requires strict quality control and layout standard during construction. Hence before a provision is made in the dam section its necessity should be utmost established.

B. The Revised design in the Detail design

The concerns of the basic design were as below:

- The grout curtain was attached to riprap which is a very permeable layer. Therefore, the seepage flow easily passes over the curtain through the rip rap.
- The lime treated soil has placed on upstream of filter and the seepage can move the lime particles into the chimney filter and it leads to filter’s malfunction in long term.
- Seepage analysis indicates that maximum hydraulic gradient in dambody reaches to 0.90 and it facilitates foundation erosion. Moreover, the embankment length is very long and high permeable layers may exist in some parts of the foundation to provide the erosion risk.
- Riprap has placed directly on lime treated layer and a riprap bed is needed to prevent washing the internal layers through the voids of the riprap.
- There is a possibility of increasing the pore pressure in the saturated materials of the dam body and foundation in earthquake condition and this issue can thread the stability of the dam.

The basic design was improved in the detail design according to the above concerns as below:

- A core trench with a width of 6 m was added to the foundation in the axis of dam. The depth of core trench depended on GSI value of the rock in which the weather rock with GSI<30 would be removed and replaced with embankment material. Nonetheless, the maximum depth of the trench was limited to 6m based on the seepage sensitivity analysis.
- Lime treated clay was replaced by riprap bed. Lime treated zones upstream of the filter can be dangerous. The combination of lime treatment with filters is not suitable for earth dams, because there will be a risk of cementing the filters.
- Consolidation grouting spacing 3 m in 3 rows was added into the foundation treatment in the core trench area.

- Grout curtain (one row with 3 m spacing) moved from upstream toe to the core trench location in the middle of the consolidation grouting boreholes.
- A 5 m width berm was added to upstream face
- A 0.3 m drain layer was considered inside the horizontal filter blanket in downstream of chimney filter
- Concrete plinth and sealing layer was placed on the foundation of core trench
- Riprap size increase from 1m to 1.8 m and thickness of riprap layer change from 1 to 3 m based on the wave height calculation as per the USBR code.
- Concrete Parapet changed to gabion parapet to create flexible movement due to possible settlement in the riprap layer. A 30% damages was deemed in the calculation of the riprap maximum size due to non-practical size of the riprap without this assumption. Therefore there was a risk of collapsing in the concrete rigid parapet by the settlement of the riprap layer.

The cross section of detail design studies is shown in Figure 3.

Horizontal Filter blanket (Base Filter) is provided in the downstream portion of the dam to collect seepage from chimney filter, trench filter, body of the dam to the downstream toe trench. USBR (2011) has proposed filtering criteria for maximum D15F to be maximum 0.5 mm for dispersive soil. In view of the potential dispersive nature of the core material, the maximum d15 size of the fine filter has been set at 0.5mm rather than 0.7mm as adopted for non-dispersive core material. A drain with thickness of 30 cm has been set inside the filter blanket for 2/3 of downstream length from chimney filter. This precaution has been considered to increase the filtering capability of the blanket and decrease the gradient of seepage in downstream parts of chimney filter. On the other hand, the nonlinear dynamic analysis of the dam shows potential of shear displacement in the foundation near to chimney filter. Therefore, the filter drain has been avoided in 1/3 of the filter blanket length near to chimney filter due to settlement potential and risk of erosion of dispersive soil through the drain. The total thickness of filer blanket is 1 m and ended to toe trench. Toe-trench collects water seeping through body of the dam and leads it to natural drainage system. Upstream Slope Protection is ensured by providing riprap against the water wave energy. For design of the riprap, USBR Code was used considering maximum possible fetch length of 23 mil and maximum wind speed of 87.5 MPH. This inputs have resulted a maximum riprap size of 1800 mm with layer thickness of 3 m.

5. Precaution In Stability Analysis

Reduction of shear strength and loss of cohesion of materials at low stress levels are serious problems of dispersive materials. Therefore, the resistance of this type of material at the surface of the slope will be very low. So, a “Bi-Linear Shear Failure Envelope” has been considered in order to take into account the non-linearity of shear strength of soil and potential for over estimation of shear strength at low confining stresses as typically shown in Figure 4. The strength envelopes derived from the geotechnical investigations were therefore modified with the strength envelope taken to the point of origin from a normal stress of 75 kPa. The correction eliminates any un-conservatism with shallow failure surfaces.

The batter slopes and the internal zoning of the dam have been designed by trial to determine the optimal arrangement. The analyses show that all results meet the required factor of safety for the static analyses. Stability check of the submitted design (U/S slope of 1:2.3 with 10 m-berm) indicates that by using more appropriate bi-linear shear strength envelope, it is needed to consider the 10 m-berm with upstream slope of 1:2.3

The standard method of evaluating the safety of embankment dams against sliding during earthquakes has been checked by the pseudo-static method for a dam with no soils subject to liquefaction. A horizontal acceleration equivalent of 0.5 PGA (Peak Ground Acceleration) is used with any potential strength reduction associated with strain weakening applied. The method is empirical with a factor of safety less than 1.0 indicating that large deformations of the embankment are possible. A horizontal load of 50% of the PGA (K_h= 0.15g) was included as the pseudo-static acceleration in the normal water level models. The seismic deformations of the dam were in an acceptable range. Possible dynamic displacement is investigated by nonlinear dynamic analysis and the results has been incorporated in the design with thickened filter zones in areas of possible high shear. The permanent deformation of the dam that does not compromise the available freeboard of the embankments, is acceptable.

6. Seepage Analysis And Filter Design

A seepage analysis was performed to evaluate the hydraulic gradient and the total amount of leakage through the dam body and foundation for normal water level. The permeability of the chimney & blanket filter was estimated based on the Hazen's equation ($k=0.01x\ D_{10}^2$) where k is the permeability in m/sec and D10 is the particle size in which 10% of the filter is finer in millimeters. For the average value of D10 (0.23mm), the permeability obtained is 5e-4 m/s. The minimum D10 value of the drainage material is about 4 mm. According to the above equation, the permeability of the drainage layer is likely more than 0.16 m/s. To be conservative, the permeability of the horizontal drainage layer was adopted as 0.05 m/s.

The maximum gradient through the dam body is in the core trench, with a gradient higher than 1.1. In the overburden downstream of the core trench, the hydraulic gradient is less than 0.1, however, the allowable gradient should be less than 0.25 without a protection filter. Therefore, the risk of internal erosion is high and all of flow paths should be protected by filter. Due to the risk of cracking in the concrete plinth, it is necessary to implement a flexible sealing layer on the concrete plinth. The top of the chimney filter has been considered a few meters higher than the required value from the results of the seepage analysis. The upper parts of the dambody is usually dry and risk of desiccation cracking is high in these areas.

The seepage analysis was repeated by increasing the filter blanket thickness from 0.6 m to 1 m. The hydraulic gradient slightly higher than desired pore pressures are developed in the downstream shoulder in the NWL case. A drainage layer whose permeability is at least 100 times of the filter, was added in half the length of blanket. The seepage analysis result as shown in Figures 5 and 6, shows the phreatic surface is within the filter with a half drainage layer and only slightly above for the conservative PMF case. The full development of steady state conditions for the PMF case is considered unlikely and the phreatic surface is marginally above the top of filter, but this is considered to be acceptable.

A full width drainage layer may reduce the pore pressures further, however; shear through the dam near the base of the chimney is a risk to the dam in the earthquake condition. Therefore, the drainage blanket was stopped short to mitigate the risk of shear exposing the drainage material to the clayey fill and allowing piping into this layer. Based on the sensitivity analyses, the 1m thick blanket with drainage layer in 2/3 length of filter blanket is sufficient to control seepage through the embankment and mitigates the risk of the filter zones being sheared.

7. Conclusion

There is no suitable materials in many dam projects or the costs of producing and transporting suitable materials are very high. In such cases, the use of available materials, even dispersive, is unobstructed by imposing some technical precautions in the design and construction. These points can be summarized as follows:

- All possible paths of erosion in the body and foundation must be well filtered.
- Joints and cracks in the foundation must be consolidated as much as possible.
- Materials in the borrow area should be identified and stockpiled as much as possible.

- The chemicals treatment include hydrated lime, alum, fly ash, gypsum, agricultural lime, magnesium chloride, and mixtures of hydrated lime with agricultural lime can be used for reducing dispersivity potential. These methods are more suitable for protecting surfaces and slopes against rain. Modification of limited zones of the embankment is not safe against internal seepage and erosion because the treated materials can be easily cracked and therefore the erosion potential increases in other parts of embankment.
- The combination of soil remediation and the use of filter are not common, because some part of lime or other stabilizing materials may gradually dissolve and cause the filters to clog or cemented.
- To reduce permeability and avoid cracking, the compaction moisture content should be higher than the optimum moisture content.
- The design criteria of the filter should be based on the dispersivity of the material.
- The thickness of the filter should be considered in such a way that the required thickness is maintained due to possible shear displacements. This type of displacement can occur due to heterogeneous subsidence or displacement of sliding wedges during an earthquake.

8. Declarations

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Availability of data and material: No problem, It can be shared as attachments of the article after confirming for publication.

Code availability: Not applicable

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Ethics approval: Hereby, I Ali Heidari consciously assure that for the manuscript " Embankment dam design with dispersive soil: Solutions and Challenges" the following is fulfilled:

1) This material is the authors' own original work, which has not been previously published elsewhere.

2) The paper is not currently being considered for publication elsewhere.

3) The paper reflects the authors' own research and analysis in a truthful and complete manner.

4) The paper properly credits the meaningful contributions of co-author and co-researchers.

5) The results are appropriately placed in the context of prior and existing research.

6) All sources used are properly disclosed (correct citation). Literally copying of text must be indicated as such by using quotation marks and giving proper reference.

7) All authors have been personally and actively involved in substantial work leading to the paper, and will take public responsibility for its content.

Author's contribution statement:

All authors contributed to the study conception and design. Mr. Salehi performed stability and seepage analysis and interpreted the results regarding the static and non-linear & dynamic stability analysis of the dam body. Dr. Heidari performed the literature review, coordination for the required geotechnical information, and the assumptions considering the design feature. He also prepared the text of the paper based on the performed analysis by Mr. Salehi.

Consent for publication:

We, Ali Heidari & Davood Salehi give our consent for the publication of identifiable details, which can include photograph(s) and/ case history and/or details within the text (“Material”) to be published in the Journal and Article. Therefore, anyone can read material published in the Journal.

9. References

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Figures

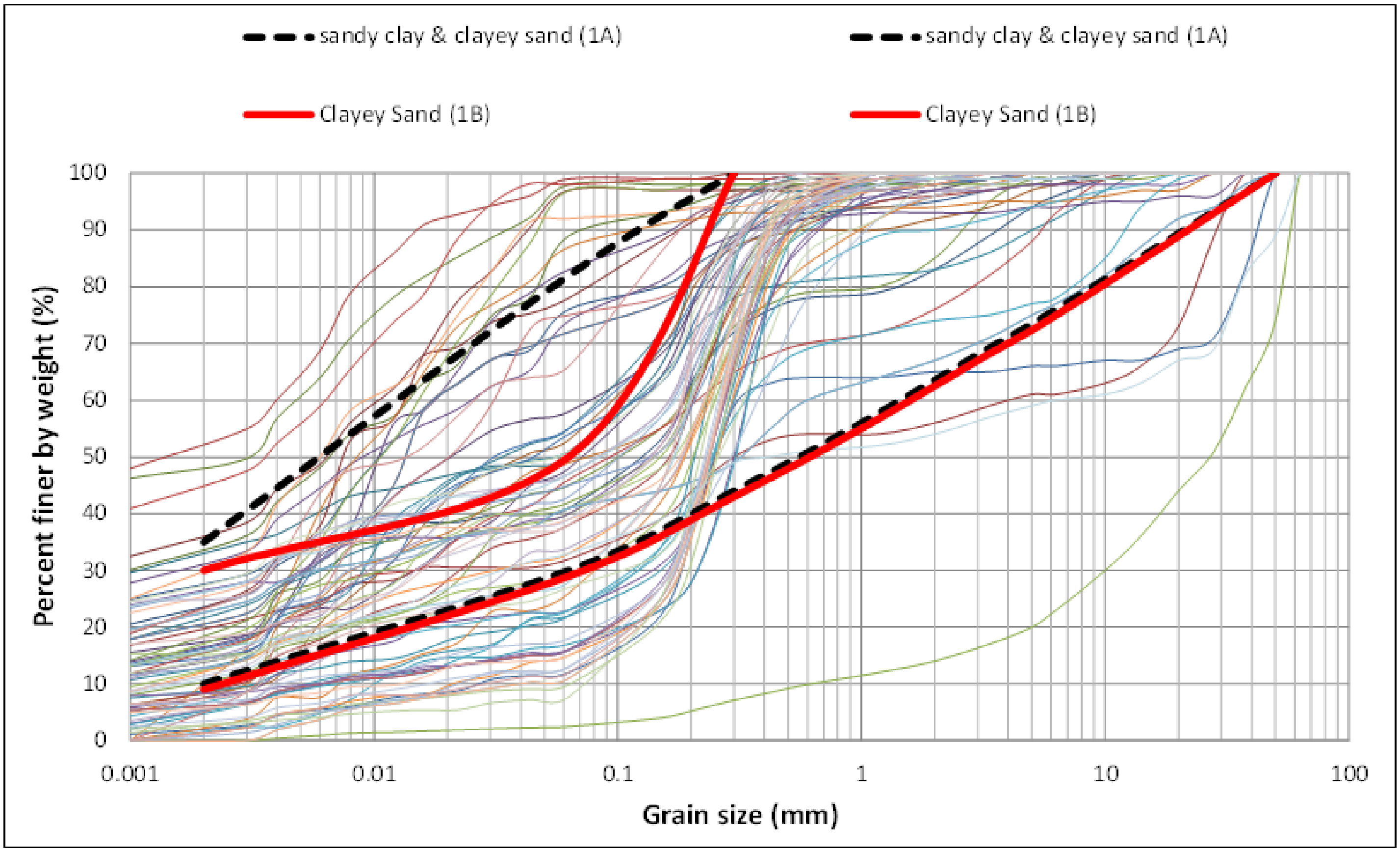

Figure 1

Gradation curves of borrow material and selected envelope

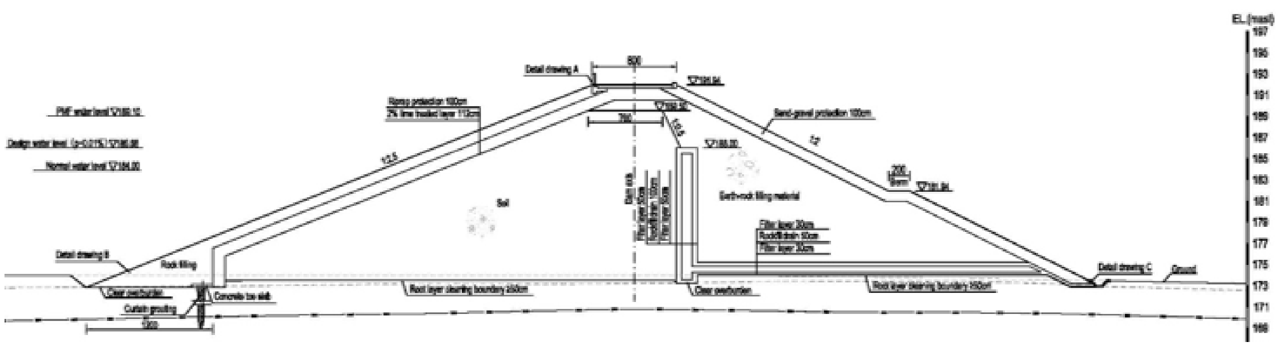

Figure 2

Cross section of the embankment in the basic design stage

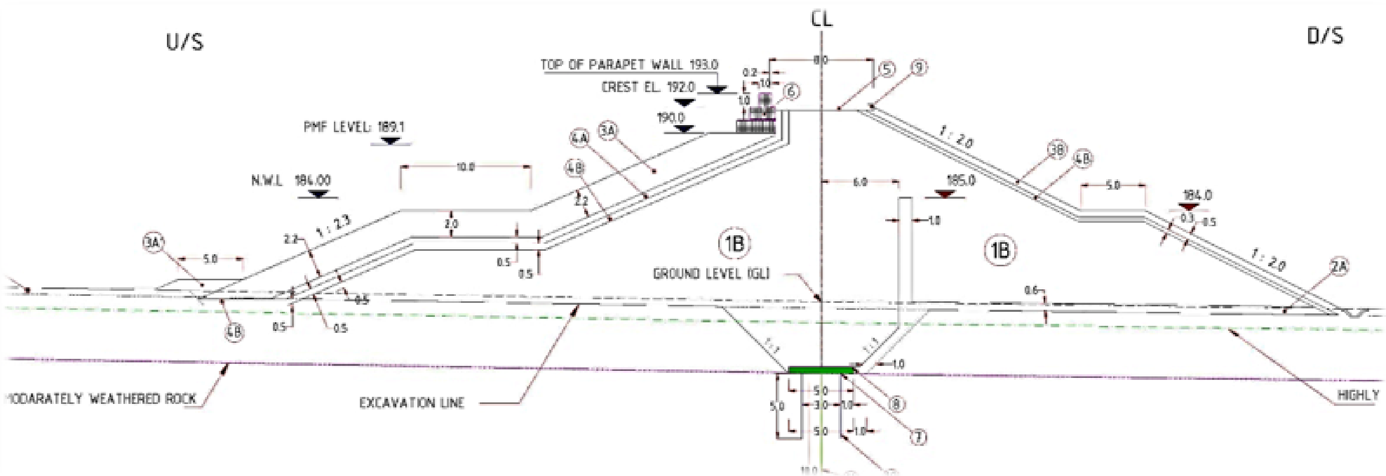

Figure 3

Cross section of embankment in the detail design

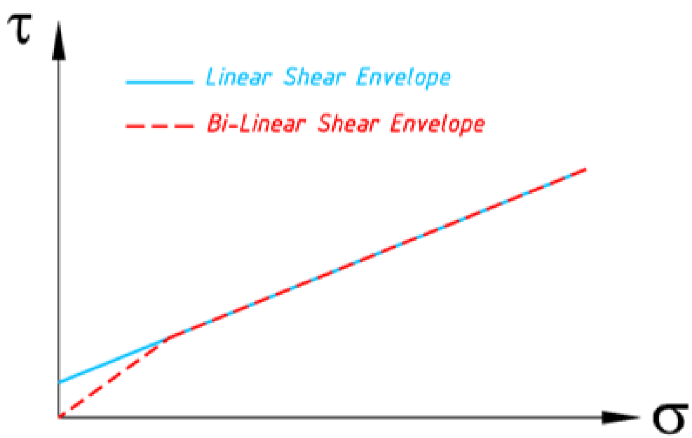

Figure 4

Linear versus Bi-Linear Shear Strength Envelope

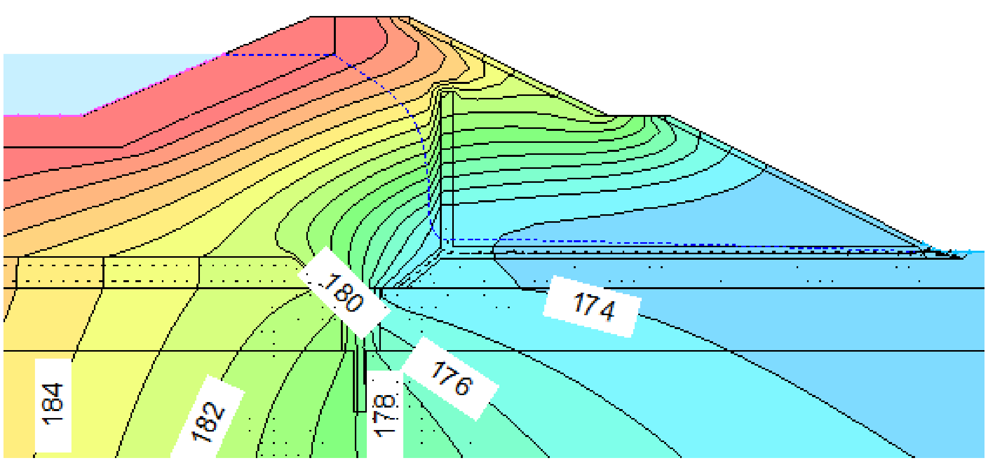

Figure 5

Seepage analysis results with filter blanket thickness of 1m – no drain (in PMF case)

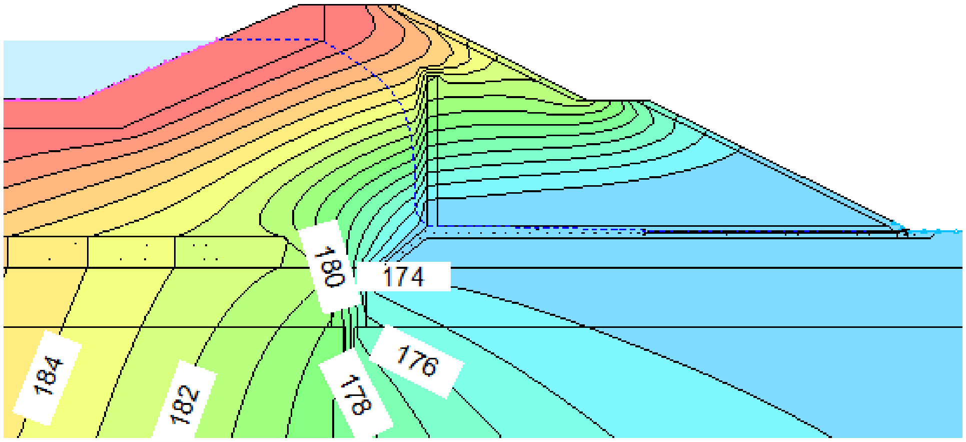

Figure 6

Seepage analysis results with blanket thickness of 1m + drain in half length of the filter (in PMF case)