

Challenges of Earthen Cofferdam in Deep Excavations for Waterfront Structures, a Case Study



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Abstract This paper is a case study of an earthen cofferdam, constructed for a deep excavation at intake location in River Aaundha, Maharashtra, India. A 12 m (39 ft) deep excavation was made to construct the intake well. The natural soil profile at this location is clay followed by rock. An earthen Cofferdam of a maximum height of 7 m (23 ft) was made around the periphery of the excavation. Cofferdam embankment and excavation slopes were analysed using the finite element software PLAXIS-2D. Clayey sand was proposed as a filling material during design, but clayey soil was used for the embankment formation during execution. The embankment was built up to 5 m in height in July 2017 and completely submerged due to monsoon. In February 2018, the embankment height was raised to 7 m (23 ft) by filling the soil over the existing submerged embankment. After a few days of completion of the Cofferdam, the inside slope of the embankment had started sliding due to continuous dewatering. The design and execution of deep excavation with earthen Cofferdam for waterfront structures are challenging. The selection of filling material for embankment formation and dewatering techniques plays a vital role in the safety and stability of the embankments. Although all the safety measures were taken during the design, execution challenges are unpredictable.

Keywords Deep excavation · Embankment · Cofferdam · Slope stability · PLAXIS · Dewatering · And sudden drawdown

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1 Introduction

Cofferdam is a temporary enclosure in or around a body of water that is constructed to allow diversion or damming of an enclosed area. The primary purpose of a Cofferdam is to create a dry working area for a structure to be executed. Cofferdams are typically conventional embankment dams of both earth- and rock-fill, although concrete or some sheet piling also may be used.

1.1 Earthen Cofferdam

This type of Cofferdam is suitable for high heads of water with low velocity. A successful Cofferdam does not need to be completely watertight because some seepage of water into the excavation is usually well tolerated. The water collected is pumped out of the excavation afterwards. The embankment is provided with a minimum freeboard of 1 m (3 ft) to prevent overtopping by waves. This type of cofferdam requires a large base area and is adopted when an area of excavation is very large. Clayey soil is appropriate for construction in the dry season. If constructed in the wet season, the clayey sand or sandy clay fill is the best material.

1.2 Safety

Embankment slope failure may occur in steady-state seepage or sudden drawdown conditions if the soil shear strength parameters are not adequate. Other factors like earthquakes may cause dam failure as referred to in IS: 7894 (1975), but considering construction duration of the structure, this failure is very rare and normally Cofferdams are not designed for earthquakes. Overtopping or overflow of an embankment dam may also cause eventual failure. It is required to provide a minimum freeboard to prevent overtopping failure as per IS: 8826 (1978).

2 Case Study

2.1 Location

The present deep excavation and Cofferdam were located near Mukane Dam on the Aaundha River, Nashik district in the state of Maharashtra in India.

2.2 Physiography

The topography of the area: Uneven, Soil Type: Black cotton soil followed by Basalt rock.

Climate: tropical wet and dry climate.

2.3 Cofferdam and Excavation Details

Natural ground level = varies from average RL + 581 m to RL + 587 m.

High flood level = RL + 594 m.

Average water level = RL + 587 m.

Cofferdam top level = RL + 588 m.

Cofferdam top width = 4 m (13 ft).

Slope of the Cofferdam = 1V:3H (Underwater formation)

The bottom level of the excavation = RL + 575 m.

Excavation slope in clay = 1V:1H, Excavation slope in rock = 3V:1H.

3 Geotechnical Study

3.1 Subsoil Exploration

Four number of boreholes were taken at specified locations to ascertain the information about the sub-soil, its nature and its strength (Table 1). Soil samples were collected at different depths to identify the soil strata and to conduct laboratory tests. The water table was encountered at ground level.

Table 1 Natural ground profile and shear strength parameters

Soil layers	From (m)	To (m)	γ (kN/m ³)	c (kN/m ²)	ϕ°	UCS (kN/m ²)	Es (kN/m ²)
Clay (CH)	0	-6	17	75	0	-	6600
Clayey sand (SC)	-6	-9	17.5	70	20	-	32,500
Grey basalt	-9	-12	24	-	-	1.385×10^4	20×10^5
Dark basalt	-12	-20	25	-	-	1.533×10^4	30×10^5

3.2 Laboratory Testing

Appropriate laboratory tests were conducted based on IS: 2720 (2006–07). The main tests conducted are listed below.

Tests on Borehole Samples

- Grain size analysis, Atterberg limits (Liquid limit and Plastic limit).
- Natural moisture content, Bulk density.
- Chemical tests on soil and water.
- Un-confined compressive strength on Rock, Triaxial test for determining (c & ϕ).

4 Analysis

Based on the geotechnical investigation report slope stability analyses were done for the embankment and excavation together by PLAXIS-2D.

4.1 Introduction to PLAXIS-2D (2014)

PLAXIS is a finite element package that has been developed, especially for the analysis of deformation and stability in geotechnical engineering projects.

4.2 Analysis with PLAXIS-2D

Cofferdam embankment was analysed considering clayey sand (refer to Table 2) as filling material. Embankment along with excavation was simulated with PLAXIS software for steady-state seepage condition and sudden drawdown condition. Mohr–Coulomb constitutive model and drained shear strength parameters were used in the analysis. The critical slip circle was observed in the downstream side in case of a steady-state condition (Fig. 1), whereas, in sudden drawdown, it was observed in the upstream side (Fig. 2). Minimum factor of safety required for steady-state seepage and sudden drawdown condition was 1.5 and 1.3, respectively, as per IS: 7894. Refer to Table 3 for analysis results (Figs. 3 and 4).

Table 2 Cofferdam filling soil properties

Type of soil	From (m)	To (m)	γ (kN/m ³)	c (kN/m ²)	ϕ°	UCS (kN/m ²)	Es (kN/m ²)
Clayey sand (proposed)	0	7	18	10	30	–	15,000
Clay (actual)	0	7	17	30	10	–	4800

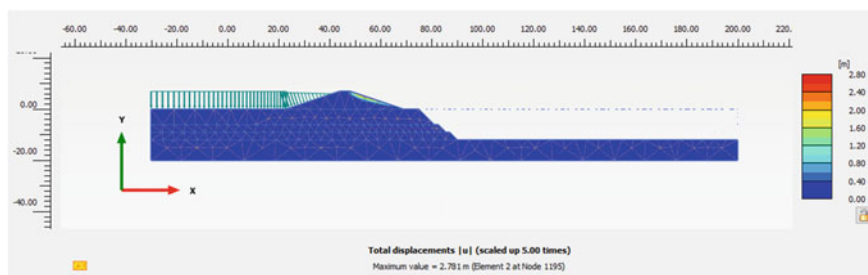


Fig. 1 Critical slip circle in steady-state seepage condition

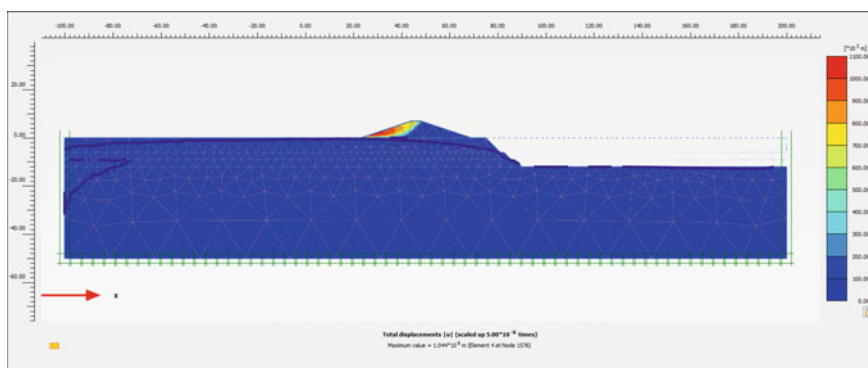


Fig. 2 Critical slip circle in sudden drawdown condition

Table 3 Slope stability analysis results of proposed fill material used for Cofferdam

Type of fill material	The factor of safety in steady-state seepage condition	The factor of safety in sudden drawdown condition
Clayey sand	1.78	3.7

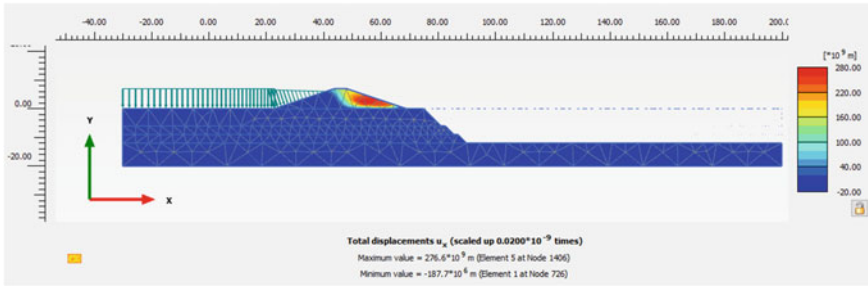


Fig. 3 Critical slip circle in steady-state seepage condition under safety analysis

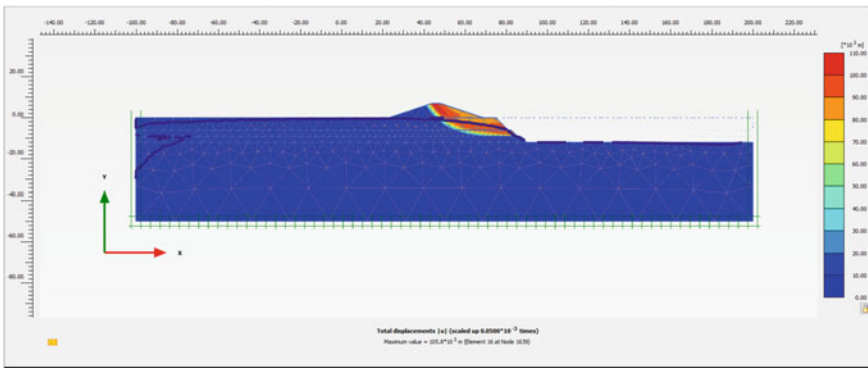


Fig. 4 Critical slip circle in sudden drawdown condition under safety analysis

5 Chronology and Challenges

5.1 Non-Availability of Proposed Filling Material at Nearby Vicinity

Clayey sand proposed for embankment formation and design was also made accordingly. Project location was surrounded by black cotton soil; hence, the Cofferdam was made with available clayey soil. Borrowed soil for embankment formation is indicated in Fig. 5.

5.2 Difficulties in Compaction

The soil was dumped into the water for embankment formation, it was not possible to compact the soil under water. Roller compaction was done once the Cofferdam

Fig. 5 Borrowed soil for embankment formation



top level reached above water level. Therefore, embankment soil under the water was not compacted.

5.3 Submergence of Cofferdam

The embankment was built up to 5 m in height in July 2017 and completely submerged due to monsoon. In February 2018, embankment height was raised to 7 m (23 ft) by filling the soil over the existing submerged embankment.

5.4 Continuous Dewatering

After completion of the embankment formation, immediately dewatering was started with six numbers of 60 HP pumps and the water level in the inside pool was reduced from RL + 587 m to +581 m within 7 days. On the eighth day inside slope, embankment soil had started sliding slowly downstream (Fig. 6).

5.5 Checking Stability of the Cofferdam with Actual Soil (Clay) as Fill Material

Slope stability analysis was performed again with filled soil as clay (Table 2) to understand the probable causes for the failure. Refer to Table 4 for analysis results.

Probable reasons for the failure

- (a) The Cofferdam was designed as the proposed fill material such as clayey sand, but the actual Cofferdam was made with clayey soil.
- (b) The embankment was constructed in two seasons, in the first season, it was submerged and in the next season, embankment was made over the existing

Fig. 6 Soil is prone to slide at downstream



Table 4 Slope stability analysis results of proposed fill material for Cofferdam

Type of fill material	The factor of safety in steady-state seepage condition	The factor of safety in sudden drawdown condition
Clay	3.36	4.8

submerged embankment. The soil became very soft due to submergence and a weak interface had developed between the submerged embankment and dry embankment.

- (c) Continuous dewatering resulted in sudden drawdown conditions and excessive pore water pressure developed in the embankment, finally led to downstream side soil sliding.

Remedy

- (a) Dewatering was stopped immediately after the sliding was observed.
 (b) The embankment was strengthened by increasing the top width from 4 m (13 ft) to 7 m (23 ft).
 (c) Proper Compaction was done by Roller (Fig. 7).
 (d) Downstream side soil was prone to slide was removed completely (Fig. 8).
 (e) The excavation was started after 15 days, as the water level reduced on the upstream side due to the summer season has begun.
 (f) The project was completed in the same season and Cofferdam was removed.

Fig. 7 Roller compaction of soil filled on upstream side



Fig. 8 Removing the soil, prone to slide



6 Summary and Conclusions

This paper elaborated on the design, analysis method, and execution challenges of deep excavations for waterfront structures. Although proper care was taken during design, execution challenges are unpredictable. Following are the learning experiences:

- i. Cofferdam shall be constructed up to the desired level in one season to avoid the maximum possible submergence.
- ii. While designing the earthen Cofferdam, designer should check the availability of filling material nearby project sites to avoid the changes from design to execution.
- iii. Continuous dewatering causes sudden drawdown conditions in embankments made with clayey soils which may lead to slip circle failure.
- iv. The selection of filling material for Cofferdam, compaction procedure and dewatering techniques play a vital role in the completion of the project on time.
- v. Also, it is advisable to provide HDPE sheet on upstream side of the embankment to control seepage during excavation.

References

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