Summary Report on Geotechnical Aspects and Dam Design

Geotechnical strata

To enable a systematic study of the proposed site, the entire length of the dam is divided into 7 zones of which one zone lies in the intertidal region in Bhavnagar, 4 zones lie in the Gulf region, 1 zone falls in the Spillway region and the remaining 1 zone lies in the intertidal and tidal land region in Dahej (**Figure 1.1**).

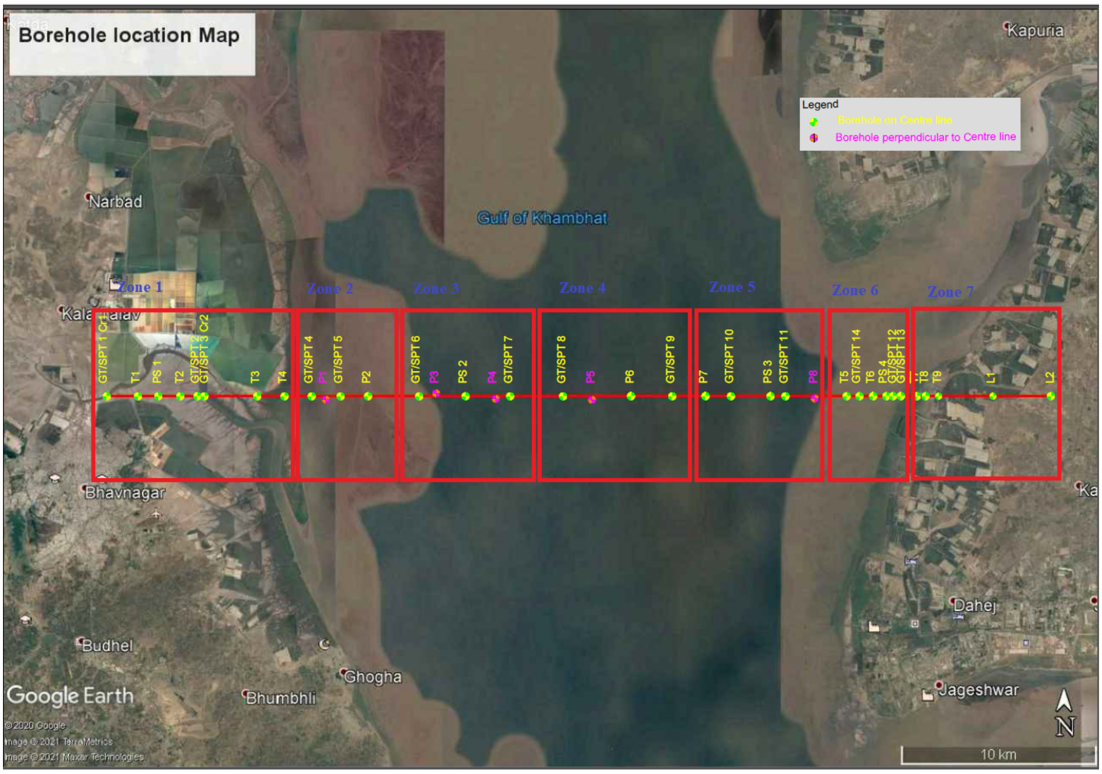

Figure. 1.1 Borehole locations on the map (*Source: COMACOE*)

The examination and study of subsoil strata reveals that very soft to soft clay is present in zones 1, 6 and 7. The thickness of soft clay layers usually varies between 2-5 metres, however a very soft clay stratum of nearly 7 m thickness was encountered in borehole T1 spanning between a depth of about 2-9 metres from the EGL. The gulf region comprising zones 2, 3, 4 and 5 is formed of dense to very dense sand layers at greater depths. Loose sand strata as well as thin layers of clay and pockets of firm to very stiff, hard silt layers were also encountered in these zones.

In case of zones 1, 6 and 7 with predominant presence of clay strata, the *c* value of soft clay varies in the range of 5 - 30 kPa. Stiffer clay strata were generally encountered towards the bottom of the boreholes with a few exceptions where firm to stiff strata was observed in layers closer to the EGL. The *c* value of such layers varied between 70 - 200 kPa in most cases. For sand strata frequent in Gulf region in zones 2, 3, 4 and 5; value of *φ'* was noted around 28-35º. A few exceptions from the above-mentioned ranges were also observed.

In zone-1, it was observed that soil strata at deeper depths were generally under consolidated while over consolidated layers was reported generally closer to the ground surface. Further in zone-6, similar observations were made. Zone-7 comprised of over consolidated soil layers while zones 2, 3, 4 and 5 marked presence of thin bands/pockets of under consolidated clay strata embedded in sand at different depths.

Thus, presence of layers of soft clay and very loose to loose silty sand layers in top soil strata may cause excessive settlements. It also emphasizes that suitable ground improvement schemes may be adopted to mitigate the ground settlement and improve the bearing capacity.

COMACOE Recommendations (COMACOE Report)

a. **Zone-1**: Soil conditions are predominantly clayey in nature with presence of pockets of fine sand. The low bearing capacity aided by excessive settlements emphasize the need for ground improvement.

b. **Zone-2, 3, 4 and 5:** Soil conditions are predominantly sandy in nature, pockets of silty clay were noted at few depths. The low bearing capacity aided by excessive settlements emphasize the need for ground improvement.

c. **Zone-6**: Soil conditions in this zone are clayey in nature with certain zones of silty sand. The excessive settlements along with low bearing capacity emphasize the need for ground improvement.

d. **Zone-7**: Clayey soil strata are observed with top layers mostly comprising CLAY of high plasticity The low bearing capacity aided by excessive settlements emphasize the need for ground improvement.

Liquefaction potential assessment

The liquefaction potential assessment of cohesionless soil in dam site is carried out as per Boulanger and Idriss (2014). The results are also compared using procedures given in IS 1893 (Part 1): 2016 and Eurocode 8 (Part 5): 2004. As there are no established procedures to evaluate liquefaction potential of cohesive soils, the assessment is carried out using criteria as per Seed et al. (2003).

Based on the liquefaction assessment, it is found that, soil in the boreholes in zones with predominant cohesive soils are safe against liquefaction under maximum ground acceleration of 0.26 and 0.40 g and earthquake magnitude of 6.3. In case of boreholes with cohesionless soils, the soil in boreholes of zones with loose to medium dense sandy or silty sand soil are susceptible to liquefaction over entire depth of assessment. In case of boreholes with medium dense to dense sandy or silty sand soil layers, the liquefaction susceptibility is seen up to 6 to 12 m and in some case up to 18 m for maximum ground acceleration of 0.26 g. However, for maximum ground acceleration of 0.40 g, the liquefaction susceptibility is seen up to entire depth of assessment especially in Zone 2 and 3 of gulf region. Summary of the liquefaction analysis is presented in **Table 1.1.**

Extent of ground improvement required

The factor of safety against liquefaction susceptibility depends on the SPT N value observed in the field. If the SPT N value of the existing ground is improved sufficiently enough to make the factor of safety greater than one, the soil becomes safe against liquefaction. **Table 1.2** gives the SPT N values along the depth for all the boreholes for the soil to be non-liquefiable. It is observed that, for depth up to 10 m, the SPT N value of 25 ensures safety.

Table 1.1. Summary of liquefaction analysis

Borehole No.	Potentially liquefiable layers	
	PGA = 0.26 g	PGA = 0.40 g
Zone 1 – Intertidal region at Bhavnagar		
T1	--	--
T2	--	--
T3	--	--
T4	3-6 m, 9-12 m	0.5-15 m
GT-SPT2	--	--
GT-SPT3	1-3 m	1-6 m
Zone 2 – Channel A in Gulf region		
GT-SPT4	1-9 m, 15-20 m	1-12 m, 15-20 m
GT-SPT5	1-9 m, 12-20 m	1-9 m, 12-20 m
Zone 3 – Channel B in Gulf region		
GT-SPT6	1-6 m	1-6 m
GT-SPT7	1-6 m, 9-18 m	1-20 m
Zone 4 – Channel C in Gulf region		
GT-SPT8	1-3 m	1-3 m
GT-SPT9	--	1-3 m, 6-15 m
Zone 5 – Channel D in Gulf region		
GT-SPT10	1-3 m	1-6 m
GT-SPT11	--	4.5-7.5 m
Zone 6 – Spillway area		
GT-SPT12	--	--
GT-SPT13	1.5-4.5 m	1.5-4.5 m
GT-SPT14	1-3 m	1-3 m

T5	1-3 m	1-3 m
T6	1-3 m	1-3 m
Zone 7 – Intertidal & Land Region at Dahej		
T7	--	
T8	9-12 m	6-12 m
T9	--	9-12 m
L1	--	--
L2	--	--

Table 1.2. SPT N value required for safety against liquefaction

Borehole No.	Depth (m	Soil type	SPT N value (observed)	FS (Boulanger and Idriss, 2014)		SPT N value (Required for FS>1)	
				PGA = 0.26 g	PGA = 0.4 g	PGA = 0.26 g	PGA = 0.4 g
Zone 1 – Intertidal region at Bhavnagar							
T4	0.5	SM	16	1.05	0.68		21
	3	SM	14	0.98	0.64	15	20
	6	SM	16	1.06	0.69		22
	9	SM	16	0.96	0.63	17	25
	12	SM	24	1.43	0.93		26
	15	SM	50	Safe	Safe		
GT-SPT3	1	SM	7	0.56	0.36	17	21
	3	SM	17	1.21	0.79		20
Zone 2 – Channel A in Gulf region							
GT-SPT4	1	SM	7	0.56	0.36	18	22
	3	SM	8	0.61	0.39	16	23
	6	SM	10	0.69	0.45	17	25
	9	SM	20	1.09	0.71		29

	12	SM	28	1.39	0.90		31
	15	SM	12	0.76	0.50	20	33
	18	SM	16	0.96	0.62	17	32
GT-SPT5	1	SM	7	0.45	0.30	20	25
	3	SM	8	0.66	0.43	15	20
	6	SM	10	0.76	0.49	15	22
	9	SM	25	1.08	0.71		31
	12	SP-SM	23	0.96	0.63	24	32
	15	SP-SM	17	0.74	0.48	25	35
	18	SP-SM	16	0.80	0.52	23	33
Zone 3 – Channel B in Gulf region							
GT-SPT6	1	SP	8	0.45	0.30	21	26
	3	SP-SM	10	0.57	0.37	20	26
	6	SP-SM	30	1.90	1.23		
	9	--	32	1.60	1.05		
	12	SP	46	Safe	Safe		
	15	SP	R	Safe	Safe		
	18	--	68	Safe	Safe		
GT-SPT7	1	SP	10	0.56	0.36	20	25
	3	SM	13	0.70	0.61	20	26
	6	SM	16	1.04	0.67		22
	9	SM	13	0.77	0.54	20	27
	12	SM	18	0.95	0.62	20	28
	15	SM	17	0.90	0.59	20	30
	18	SM	26	1.26	0.82		31
Zone 4 – Channel C in Gulf region							
GT-SPT8	1.5	SP	16	0.76	0.50	21	25
	4.5	SP	35	3.31	2.15		
	7.5	SM	32	4.79	3.11		
	10.5	SM	35	3.32	2.16		
	13.5	SM	37	4.20	2.73		
	16.5	SM	42	4.58	2.98		
	19.5	SP-SM	41	2.18	1.42		
GT-SPT9	1	SP-SM	18	1.10	0.72		22
	3	SM	34	Safe	Safe		
	6	SM	16	1.06	0.69		21
	9	SM	21	1.21	0.79		25
	12	SM	23	1.37	0.89		25
	15	SM	54	Safe	Safe		
	18	SP-SM	36	1.59	1.03		
Zone 5 – Channel D in Gulf region							
GT-SPT10	1	SM	10	0.64	0.42	17	22
	3	SM	16	1.08	0.70		20
	6	SM	48	Safe	Safe		

	9	SM	56	Safe	Safe		
	12	SM	72	Safe	Safe		
	15	SM	56	Safe	Safe		
	18	SM	108	Safe	Safe		
GT-SPT11	1.5	SM	22	1.77	1.15		
	4.5	SP-SM	27	1.50	0.98		28
	7.5	SM	29	1.54	1.97		
	10.5	SM	51	Safe	Safe		
	13.5	SP	67	Safe	Safe		
	16.5	--	74	Safe	Safe		
	19.5	--	78	Safe	Safe		
Zone 6 – Spillway area							
GT-SPT12	1	SM	34	Safe	Safe		
GT-SPT13	1.5	SM	13	0.81	0.53	16	21
	13.5	SM	44	Safe	Safe		
GT-SPT14	1	SM	16	0.99	0.64	17	21
T5	1	SM	9	0.64	0.42	16	21
T6	1	SM	11	0.53	0.35	21	26
Zone 7 – Intertidal & Land Region at Dahej							
T7	6	SM	18	1.21	0.78		21
	9	SM	21	1.27	0.83		24
T8	6	SM	21	1.70	1.11		
	9	SM	11	0.73	0.47	18	24

Analysis and design of dam at Gulf region

The cross sections for the dam are idealised based on the cross sections proposed by the NIOT and CWPRS studies. Based on the NIOT recommendation initially, a slope of 1:2 is adopted on the reservoir side and safety analysis to assess the stability of the dam is carried out considering live load and pseudo static load. A factor of safety value of less than one was observed for pseudo static case with peak ground acceleration (PGA) 0.26 g. Also, the horizontal displacements were more on the reservoir side slope of the sandfill. Based on these observations, a slope of 1:3 is adopted on the reservoir side for the sandfill and 1 m thick rock fill used as the base for the entire stretch at the base of the pavement, as shown in **Figure 1.2**. The results of the analysis are discussed in detail in section pertaining to results and discussions.

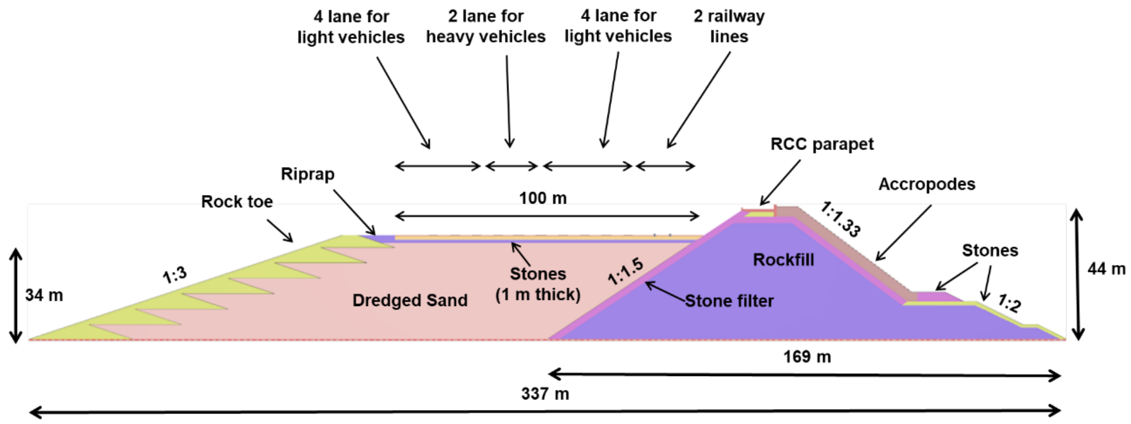

Figure 1.2. Final cross section of the dam for -25 m sea bed level

Geotechnical Parameters

Borehole data (GT/SPT 4) which have relatively weak geotechnical parameters is used for the present work (**Table 1.3**). The shear strength parameters are adopted based on the geotechnical test reports of COMACOE. The modulus value of sandy soil is computed from SPT N value based on Schultze and Muhs (1967) and of clayey soil is based on the CIRIA - Report 143. (1995). The ground improvement by vibro-compaction is proposed for the top 6 m. Hence, an improved value is adopted for the modulus in the top 6 m.

Table 1.3. Material properties of the subsoil used in FE modelling (corresponds to GTSPT 7)

Depth (m)	Unit weight, γ (kN/m^3)	Young's modulus, E (MPa)	Poisson's ratio, ν	Cohesion, c (kPa)	Friction angle, ϕ (degrees)	Dilatancy angle, ψ (degrees)	Coefficient of permeability, K	
							(m/day)	(cm/s)
0-1.6	22.08	50	0.3300	2	32	0	0.01673	1.93E-05
1.6-4.55	20.39	50	0.35	2	32	0	2.58E-3	2.98E-06
4.55-6	20.77	50	0.35	17	32	0	0.01673	1.93E-05
6-7.5	21	50	0.33	17	32	0	0.2624	3.03E-04
7.5-9	21	50	0.33	2	30	0	0.2624	3.03E-04
9-10.5	21	50	0.33	2	30	0	0.2624	3.03E-04
10.5-12	21	50	0.35	2	30	0	0.2624	3.03E-04
12-13.5	21	50	0.3	2	30	0	0.2624	3.03E-04
13.5-15	18	50	0.3	5	35	0	0.751E-3	8.69E-07
15-16.5	19.56	50	0.33	5	35	0	0.2624	3.03E-04
16.5-18	19.56	59	0.33	19	35	0	0.01517 E-3	1.75E-08
18-19.5	19.6	59	0.33	19	35	0	0.751E-3	8.69E-07
19.5-21	20.28	72	0.33	0	33	0	0.1517E-3	1.75E-07
21-22.5	20.28	72	0.33	0	33	0	0.751E-3	8.69E-07
22.5-24	21.32	72	0.33	0	33	0	0.751E-3	8.69E-07

24-25.5	21.32	74	0.33	0	33	0	0.751E-3	8.69E-07
25.5-27	21.73	60	0.33	0	35	0	0.751E-3	8.69E-07
27-28.5	21.73	60	0.33	0	35	0	0.751E-3	8.69E-07
28.5-30	20.08	70	0.33	17	35	0	0.751E-3	8.69E-07
30-33	20.08	70	0.33	17	35	0	0.751E-3	8.69E-07
33-36	20.58	92	0.33	2	35	0	0.751E-3	8.69E-07
36-39	21.22	92	0.33	2	35	0	0.751E-3	8.69E-07
39-42	21.22	112	0.33	2	35	0	0.751E-3	8.69E-07
42-45	21.22	133	0.33	2	35	0	0.751E-3	8.69E-07
45-48	21.22	133	0.3	2	35	0	0.751E-3	8.69E-07
48-51	20.17	124	0.33	2	35	0	0.751E-3	8.69E-07
51-54	17.22	124	0.33	2	35	0	0.751E-3	8.69E-07
54-60	19.06	124	0.33	2	35	0	0.751E-3	8.69E-07

Results and discussion

The plastic stress-strain analysis, stability/safety analysis, seepage analysis, and dynamic analysis are carried out for 6 different cross sections of the dam in the gulf region. The dam sections are of 24 m, 29 m, 34 m, 39 m, 44 m, and 49 m high, and the corresponding reduced levels of the sea bed are -5 m, -10 m, -15 m, -20 m, -25 m, and -30 m. An initial analysis considering the gravity load and steady state seepage condition is carried out. During the initial phase, the soil stratum is activated along with water of RL +8.76 m (design water level in the sea side). Secondly, a plastic stress-strain analysis is carried out for the dam to compute the displacements. Thirdly, plastic stress-strain analysis is carried out by activating the live load of the vehicles. For all the plastic analysis, the water level considered in reservoir side is RL +3 m (Full Reservoir Level) and in sea side is +6.5 m (High Astronomical Tide Level). In fourth stage, a safety analysis is carried out considering the hydraulic conditions as in the previous stage, by strength reduction method. Then, a coupled flow analysis is carried out by considering hydrodynamic condition on the sea-side to estimate the seepage quantity. In the next stage, a pseudo-static analysis is carried out to determine the factor of safety under seismic condition. Finally, a dynamic analysis is performed by applying an acceleration time history at the base of the model to determine the seismic settlement.

Stability

The factor of safety for all the sections under static and pseudo static (0.26 g) condition with steady state seepage is presented in **Table 1.4.** All the sections considered in the present study are found to achieve a factor of safety around 1.7 to 1.9 in the static case and 1.1 - 1.4 in the dynamic case.

Table 1.4. Factor of safety of the dam of different sections for static and pseudo static case (0.26 g).

Loading Conditions	**Height of the Dam**					
	24 m	**29 m**	**34 m**	**39 m**	**44 m**	**49 m**
Static	1.9	1.9	1.9	1.9	1.9	1.9
Pseudo-Static	1.41	1.33	1.3	1.2	1.2	1.1

Displacement

The maximum and minimum amplitudes of the vertical and horizontal components of the displacements for both static and dynamic condition are presented in **Tables 1.5** and **1.6**.

Table 1.5. Amplitude of vertical displacement of the dam of different sections for static and dynamic case (0.26 g).

Vertical Displacement (mm)	**Height of the Dam**					
	24 m	**29 m**	**34 m**	**39 m**	**44 m**	**49 m**
Static **Max**	90	128.2	113	108	108	106.1
Min	-6.2	-12.7	-1.2	-2	-1.8	-1.2
Dynamic **Max**	47.5	47	92	69	423	130.2
Min	-30.7	-27	-33	-42	-128	-77.7

Table 1.6. Amplitude of horizontal displacement of the dam of different sections for static and dynamic case (0.26 g).

Horizontal Displacement (mm)	Height of the Dam					
	24 m	**29 m**	**34 m**	**39 m**	**44 m**	**49 m**
Static **Max**	-12.7	-29.7	-17.85	-19	-17	-18
Min	9.8	7.8	13	8	7.9	6.9
Dynamic **Max**	68.2	69	177.8	69	210	221
Min	-61.6	-61	0	-88	-309	-329

It is to be noted that the maximum value of the vertical displacement refers to the uplift and the minimum value refers to the settlement. Whereas for the horizontal displacement, the maximum amplitude refers to the sliding towards the sea side and minimum amplitude refers to the sliding towards the reservoir side. It can be observed from the results that the **vertical settlement ranges between -13 mm and +130 mm for static case. The amplitudes are found to be negligible as the soil stratum is predominantly silty sand and the entire settlement will happen immediately**. Similarly, the vertical settlement for dynamic case ranges between -78 mm and 130 mm. The horizontal displacement ranges between -30 mm and 8 mm for static loading; and -330 mm and 221 mm for dynamic loading.

Seepage

The seepage quantity is calculated from a fully coupled flow analysis with hydrodynamic condition in the sea side and constant water level in the reservoir side. For the hydrodynamic case the hourly variation of the tides is simulated for one day. The quantity of seepage is obtained at three different locations of the reservoir slope as shown in **Figure 1.3**.

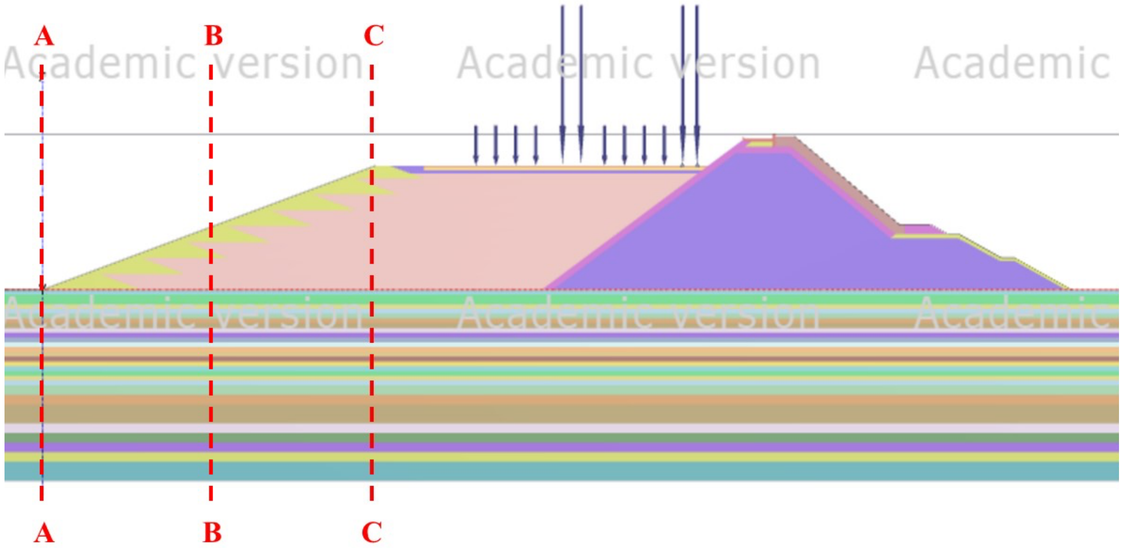

Figure 1.3. The locations in the reservoir slope where quantity of seepage is computed: Section AA – Bottom of the reservoir slope, BB – Centre of the reservoir slope, CC – Top of the reservoir slope

The seepage values computed at three different locations of the reservoir are presented in **Table 1.7**. At a particular section, the negative sign indicates flow towards reservoir side i.e. sea water seepage and it is to be noted that the higher seepage of sea water into the reservoir side is not desirable. The positive sign indicates flow towards the sea side i.e. freshwater seepage which is not a critical condition. It is observed that the seepage is less under the hydrodynamic condition. Therefore, it can be concluded that the provision of any cut-off wall is not necessary. The stone filter can be provided in between the dredged sand and rockfill only for the purpose of separation. A geosynthetic filter can be provided between the dredged sand and the rockfill for the separation of sand particles and rock fill. There is no need of gabion in the reservoir side as the seabed and dredged sand is one and the same. Also, **gabion will facilitate water seepage due to its high permeability. Therefore, gabions should not be provided at the seabed in the reservoir side.**

Table 1.7. Quantity of Seepage (m^3/day/m) at different locations of the reservoir side (AA – Bottom of Reservoir slope, BB – Centre of Reservoir slope, CC – Top of Reservoir slope)

Seepage (m^3/day/m)	Height of the Dam					
	24 m	**29 m**	**34 m**	**39 m**	**44 m**	**49 m**
AA	0.01	0.01	0.012	-0.03	0.01	0.0001
BB	-3.45	-1.58	-0.05	-15.8	0.02	-0.03
CC	-4.46	-2.18	-0.965	-18.78	- 2.7	2.2

Dynamic Analysis for Maximum Considered Earthquake

A pseudo-static and dynamic analysis is carried out for maximum considered earthquake condition to determine the factor of safety and displacements respectively. **Table 1.8.** presents the factor of safety and minimum and maximum displacements corresponding to the maximum considered earthquake of 0.4 g. The factor of safety lesser than 1 and maximum displacement of 500 mm is considered critical for the seismic condition. It can be seen from the table that the values are well within the criteria. Therefore, it can be inferred that the sections are safe against maximum considered earthquake of 0.4 g with a return period of 10,000 years.

Table 1.8. Amplitude of displacement of the dam of different sections for Dynamic case.

Analysis Results – 0.4 g			Dam height (m)					
			24 m	29 m	34 m	39 m	44 m	49 m
Settlement (mm)	Vertical Displacement	Min	79	76	73	110	-118	207
		Max	-50	-47	-46	-50.8	186	-187
	Horizontal Displacement	Min	110	111	145	100	293	330
		Max	-100	-96	-100	-50.8	-413	-450
Stability	FOS		1.15	1.06	1.09	1.07	1.001	<1

Factor of safety for the case of 49 m Dam height is reported less than 1. For this case, factor of safety after flattening of slopes (1:4) on reservoir side is 1.07. Hence, 1:4 slope on reservoir side may be considered for the locations of this 49 m dam height.

Analysis and design of dam at intertidal region

Borehole data SPT 2 and SPT 3 are considered for the present analyses which will be useful for improved properties to be achieved for adjacent boreholes.

Numerical modelling of the dam with subsoil parameters (GT/SPT 2)

The material properties of the subsoil adopted in the present investigation are listed in **Table 1.9.** The ground improvement by cement stabilization is proposed for the top 6 m. Hence, improved soil properties are adopted as shown in **Table 1.10.**

Table 1.9. Material properties of the subsoil used in FE modelling (corresponds to GTSPT 2)

Depth (m)	Unit weight, γ (kN/m^3)	Young's modulus, E (MPa)	Poisson's ratio, ν	Cohesion, c (kPa)	Friction angle, ϕ (degrees)	Dilatancy angle, ψ (degrees)	Coefficient of permeability, K	
							(m/day)	(x 10^{-5} cm/s)
0-6 m	16.9	6	0.33	16	1	0	0.06	6.9
6-10.5	16.4	19	0.3	60	16	0	0.035	4.05
10.5-13.5	18.9	53	0.33	240	1	0	0.0014	0.16
13.5-16.5	18.9	45	0.33	138	1	0	0.0014	0.16
16.5-22.5	19.5	76	0.33	21	30	0	0.009	1.04
22.5-25.5	18.6	64	0.33	200	1	0	0.023	2.66
25.5-36	20	220	0.33	5	42	0	0.035	4.05

Table 1.10. Improved material properties of the subsoil used in FE modelling (corresponds to GTSPT 2) (considering water cement ratio = 3)

Depth (m)	Unit weight, γ (kN/m^3)	Young's modulus, E (MPa)	Poisson's ratio, ν	Cohesion, c (kPa)	Friction angle, ϕ (degrees)	Dilatancy angle, ψ (degrees)	Coefficient of permeability, K	
							(m/day)	(x10^{-5} cm/s)
0-6 m	16.9	50	0.33	340	1	0	0.06	6.9

Results and discussion

The plastic stress-strain analysis, stability/safety analysis, seepage analysis, and dynamic analysis are carried out for 3 different cross sections of the dam in the gulf region. The dam sections are of 7 m, 16.5 m, 24 m high.

Stability

The factor of safety for all the sections under static and pseudo static condition with steady state seepage is presented in **Table 1.11.** All the sections considered in the present study are found to achieve a factor of safety around 2 to 3.5 in the static case and 1.5 – 2.1 in the dynamic case (**0.26 g**).

Table 1.11. Factor of safety of the dam of different sections for static and pseudo Static case (0.26 g).

Loading Conditions	**Height of the Dam**		
	7 m	**16.5 m**	**24 m**
Static	3.5	2.5	2
Pseudo-Static (0.26 g)	2.1	1.6	1.5

Displacement

The maximum and minimum amplitudes of the vertical and horizontal components of the displacements for both static and dynamic condition are presented in **Tables 1.12** and **1.13**.

Table 1.12. Amplitude of vertical displacement of the dam of different sections for static and dynamic case.

Vertical Displacement (mm)	Height of the Dam		
	7 m	**16.5 m**	**24 m**
Static **Max**	4	3	3
Min	-66	-70	-108
Dynamic **Max**	127	125	100
Min	-45	-11	-19

Table 1.13. Amplitude of horizontal displacement of the dam of different sections for static and dynamic case.

Horizontal Displacement (mm)	Height of the Dam		
	7 m	**16.5 m**	**24 m**
Static **Max**	16	12	16
Min	-19	-16	-21
Dynamic **Max**	21	150	144
Min	-240	-103	-83

It can be observed from the results that the **vertical settlement ranges between 3 mm and -108 mm for static case. The amplitudes are found to be negligible as the soil stratum is predominantly silty sand and the entire settlement will happen immediately**. Similarly, the vertical settlement for dynamic case ranges between -45 mm and 127 mm. The horizontal displacement ranges between -21 mm and 16 mm for static loading; and -240 mm and 150 mm for dynamic loading.

Seepage

The seepage quantity is calculated from a fully coupled flow analysis with hydrodynamic condition in the sea side and constant water level (FRL) in the reservoir side. For the hydrodynamic case the hourly variation of the tides is simulated for one day. The seepage values computed at three different locations of the reservoir are presented in **Table 1.14**.

Table 1.14. Quantity of Seepage (m^3/day/m) at different locations of the reservoir side (AA – Bottom of Reservoir slope, BB – Centre of Reservoir slope, CC – Top of Reservoir slope)

Seepage (m^3/day/m)	**Height of the Dam**		
	7 m	**16.5 m**	**24 m**
AA	-0.09	-0.04	-0.07
BB	-1.7	-2.6	-3
CC	-2	-3.5	-4.4

Dynamic Analysis for Maximum Considered Earthquake

A pseudo-static and dynamic analysis is carried out for maximum considered earthquake condition to determine the factor of safety and displacements respectively. **Table 1.15.** presents the factor of safety and minimum and maximum displacements corresponding to the maximum considered earthquake of 0.4 g. The factor of safety lesser than 1 and maximum displacement of 500 mm is considered critical for the seismic condition. It can be seen from the table that the values are well within the criteria. Therefore, it can be inferred that the sections are safe against maximum considered earthquake of 0.4 g with a return period of 10,000 years.

Table 1.15. Amplitude of displacement of the dam of different sections for dynamic case.

Analysis Results – 0.4 g			**Dam height (m)**		
			7 m	**16.5 m**	**24 m**
Settlement (mm)	Vertical Displacement	Min	-59	-31	32
		Max	172	195	-189
	Horizontal Displacement	Min	25	-178	-137
		Max	-341	244	238
Stability	FOS		1.4	1.04	1.07

Numerical modelling of the dam (RL – 5 m Cross section) with subsoil parameters (GT/SPT 3)

The material properties of the subsoil adopted in the present analyses are listed in **Table 1.16.** Improved material properties of the subsoil (4.5 m – 16.5 m) are listed in **Table 1.17**. RL -5 m cross section corresponding to GT/SPT 3 is considered in the following analyses.

Table 1.16. Material properties of the subsoil used in FE modelling (corresponds to GTSPT 3)

Depth (m)	Unit weight, γ (kN/m^3)	Young's modulus, E (MPa)	Poisson's ratio, ν	Cohesion, c (kPa)	Friction angle, ϕ (degrees)	Dilatancy angle, ψ (degrees)	Coefficient of permeability, K	
							(m/day)	(x 10^{-5} cm/s)
0-1.5	19	21	0.3	2.9	29	0	0.087	10
1.5-4.5	19	43	0.3	2.9	29	0	0.07	8.1
4.5-7.5	18.9	7	0.3	34	24	0	0.01	1.15
7.5-10.5	19	13	0.3	240	1	0	0.0012	0.14
10.5-13.5	19.7	16	0.3	240	1	0	0.001	0.11
13.5-16.5	18.4	20	0.3	290	1	0	0.002	0.23
16.5-19.5	17	25	0.3	240	0	0	0.006	0.69
19.5-24	19	26	0.3	211	0	0	0.01	1.15
24-30	19	41	0.3	5	30	0	0.88	101.8
30-39	17.5	14	0.3	140	0	0	0.006	0.69
39-51	18	20	0.3	184	0	0	0.016	1.85
51-57	19	67	0.3	21	29	0	1	115.7
57-63	18	26	0.3	263	0	0	0.018	2.08

63-72	17.7	31	0.3	265	0	0	0.063	7.29
72-90	18.6	50	0.3	221	0	0	0.014	1.62
90-98	19.6	39	0.3	241	0	0	0.019	2.19

Table 1.17. Improved material properties of the subsoil (4.5 m–16.5 m) used in FE modelling (corresponds to GTSPT 3) based on area replacement ratio (0.35) of stone columns

Depth (m)	Unit weight, γ (kN/m^3)	Young's modulus, E (MPa)	Poisson's ratio, ν	Cohesion, c (kPa)	Friction angle, ϕ (degrees)	Dilatancy angle, ψ (degrees)	Coefficient of permeability, K	
							(m/day)	(x 10^{-5} cm/s)
4.5-7.5	18.9	18	0.3	34	24	0	1	115.7
7.5-10.5	19	20	0.3	240	1	0	0.1	11.5
10.5-13.5	19.7	21	0.3	240	1	0	0.1	11.5
13.5-16.5	18.4	22	0.3	290	1	0	2	231.48

Staged construction

The dam is constructed in stages shown in **Figure 1.4** followed by 90 % degree of consolidation after each stage. The displacement happening at every stage of construction is shown in **Table 1.18**.

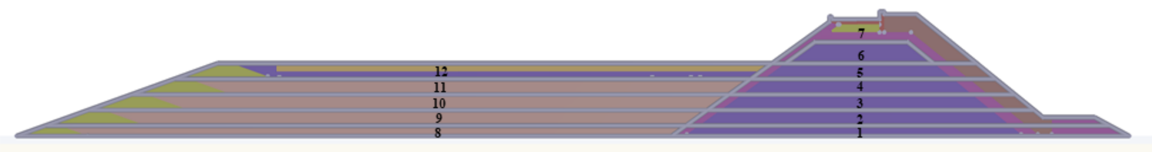

Figure 1.4. Staged construction for RL -5 m cross section (with stage numbers)

Table 1.18. Displacement at the end of each stage of construction for 44 m high dam

RL – 5 m		
Stages	**Construction settlement (mm)**	**Consolidation settlement (mm)**
1	28	26
2	42	36
3	42	32
4	42	27
5	38	23
6,7	103	46
8	24	36
9	39	49
10	41	47
11	69	74
12	91	81
13 (Live loads)	136	-

Displacement and Stability

At the end of staged construction, safety analysis is carried out and factor of safety is found to be 1.75 for static case but less than 1 for pseudo static analysis (0.26 g). Amplitude of displacement of the dam for dynamic case is shown in **Table 1.19**. Hence, improved properties (**Table 1.20**) are considered for further analyses and factors of safety are found to be 1.3 and 1.1 for 0.26 g and 0.4 g PGA respectively.

Table 1.19. Amplitude of displacement of the dam for Dynamic case

Dynamic analysis Results – 0.26 g			RL - 5 m
Settlement (mm)	Vertical Displacement	Min	-108
		Max	320
	Horizontal Displacement	Min	-126
		Max	157
Stability (pseudo static)	FOS		<1

Table 1.20. Improved material properties of the subsoil for peak ground acceleration 0.26 g and maximum considered earthquake 0.4 g

Depth (m)	Unit weight, γ (kN/m^3)	Young's modulus, E (MPa)	Poisson's ratio, ν	Cohesion, c (kPa)	Friction angle, ϕ (degrees)	Dilatancy angle, ψ (degrees)	Coefficient of permeability, K	
							(m/day)	(x 10^{-5} cm/s)
0-4.5	19	70	0.3	2	39	0	10	1157
4.5-7.5	18.9	70	0.3	34	24	0	0.5	57.85
7.5-24	17	50	0.3	380	1	0	0.006	0.69
24-30	19	41	0.3	5	30	0	0.88	101.8
30-51	17.5	50	0.3	380	1	0	0.006	0.69

Design of graded filter

Considering dredged sand as base material, filter band is designed based on USDA NRCS criterion for design of sand and gravel filters.

Graded filter between breakwater and embankment fill: (Filter 1)

1 m thick layer (Gradation 2) closer to the backfill and 2 m thick layer (Gradation 3) closer to the rockfill in order to provide a proper gradation between the larger sized rocks and sand.

Graded filter between rock toe mound and dredged embankment fill: (Filter 2)

1 m thick layer (Gradation 2) closer to the dredged backfill and 1 m thick layer (Gradation 3) between rock mound and gradation 2.

Table 1.22. Quantity of filter material with size & gradation along with filter criteria.

Material type	Total quantity (tonnes)
Filter 1	7644240
Filter 2	25905960

Table 1.23. Gradation of filters

Gradation II			Gradation III		
Sieve (mm)	Percentage passing	Selected percentage passing	Sieve (mm)	Percentage passing	Selected percentage passing
80	100	100	80	100	100
63	99-100	100	63	96-100	97
16	88-100	93	50	90-100	91
4.75	70-100	73	40	82-100	85
2.36	61-100	65	25	67-92	70
1.18	40-77	45	20	62-85	65
0.6	21-62	25	16	50-79	55
0.3	3-37	8	4.75	0-5	5
0.15	0-20	1			
0.075	0-5	0			