Design of Traditional Goan Saraswat Bunds

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Abstract. Traditional Goan Sarawsat Bunds (TGSB) are ancient embankments used for different purposes. They are extremely cost effective since they are built from materials available in the nearby locations. Their main feature is their bermed structure topped by double row of coconut trees on each side. Engineering design of an embankment from the view point of safety and economy of construction cost is a crucial but unavailable for traditional structures. Parametric studies need to be performed to assess the stability of a slope to the variation height of embankment. This paper presents the design methodology for building TGSB for various heights and the variation of factor of safety considering the effects of coconut tree root zone in the embankment for Goa region.

Keywords: Traditional Embankment Design; TGSB, Bunds.

1 Introductions

Embankments have been used since the early days of civilization as attested to both by historians and archaeologists [1]. They were mainly for the storage of water for irrigation. Some of such structures built in antiquity were of considerable size depending on purpose. They ranged from mere 1 m to 30 m or more. The earthfill dam continues to be the most common type of embankment. They are constructed using locally available materials obtained from near site excavation of earth and rock.

1.1 Traditional Goan Saraswat Bunds

Goa was reclaimed from the sea tens of thousands of years ago by Traditional Goan Saraswat Bunds (TGSB). These rubble-faced-compacted-earth retentive structures served a multitude of functions such as: network of roads interlinking the marshy fields of Goa, land reclamation, hill slope stabilizing, rainwater harvesting, flood protection, pisciculture and salt farming. Steady repair and maintenance made them survive millennia through a series of walls (Fig. 1). Today as we face a demand for sustainable infrastructure we need to study these long-established structures. Figure 2 shows some of the Traditional Goan Saraswat Bunds.

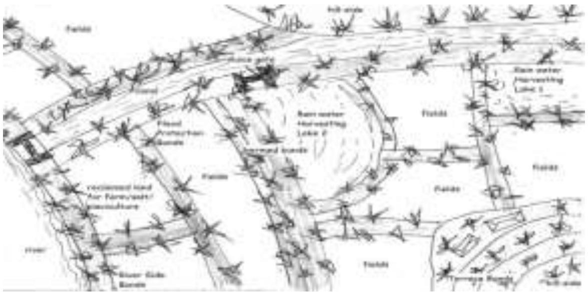

Fig.1. Uses of Traditional Goan Saraswat Bunds

The unique feature of these bunds is the double row of coconut trees planted on the top of the bunds. Several researchers [2], [3], [4] and [5] have studied the effect of vegetation on slope stability. Unlike tap root trees that need to be planted at the bottom, coconut trees are advantageous when planted on top on the embankment.

Fig. 2. Traditional Goan Saraswat Bunds

1.2 Development of embankment design

Until recently, embankment was designed by empirical means. One of the earliest to suggest analytical procedures for the slopes of embankments especially dams was Bassell in 1907 [1]. Early procedures include, meticulous preconstruction foundation investigations, thorough investigations of materials used in construction, engineering analyses and design, well planned and controlled construction methods, systematically planned instrumentation and monitoring systems. This Plan-Design-Construct-Operate-Maintain-Monitor process for an embankment is complete after it has proven itself safe during several operating cycles.

1.3 Development of TGSB design

TGSB design is mostly empirical. It follows traditional time-tested methodology. No design codes exist for such structures and hence the design procedure needs to be established from scratch. As these embankments are multi-functional and often have water on one or both sides they are to be designed as earthen dams using relevant earth-dam codes [1], [6], [7 to 15] and [16]. This paper investigates their construction methods and basic design principals and attempt to validate them by using available software.

The basic objective of TGSB design is to generate a satisfactory functional structure at a minimum total cost. They need annual maintenance for minimum maintenance costs and they use locally available materials and equipment for maintenance and repair. TGSB is safe and stable during all phases of construction and operation. Additional filters, grouting and drainage to control seepage or leakage and to protect against internal erosion may be needed as per local requirement. In earthquake regions we need to guard against the potential occurrence of cracking or displacement of the embankment during earthquakes [17]. Toe drains and relief wells are sometimes used as per the foundation requirements to guard against seepage failure [9], [12], [13] and [15].

2 Classification of Embankments

Embankments are mostly homogeneous, but they can be zoned or have a diaphragm when used as water retaining structures (Fig. 3).

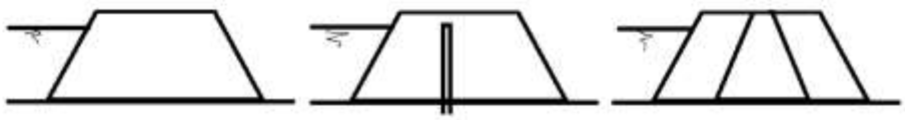

Fig.3. Homogeneous, Diaphragm and Zoned Embankments

2.1 Homogeneous Embankments

A significant number of embankment dams are homogenous embankments. These are usually constructed in areas where large amount of material with high fines are available. A purely homogeneous embankment is composed of a single kind of material (except for the slope protection) sufficiently impervious to act as a water barrier.

2.2 Zoned Embankments

Zoned dams are constructed in areas where both clays and sands, are available. These embankments use their materials best properties most beneficially to mitigate their poor properties. There is a central impervious clay/concrete core flanked by upstream and downstream vertical sand zones.

2.3 Diaphragm Embankments

They have an impervious diaphragm typically called a thin core whose position may vary from an upstream membrane, to a central cut-off, to down-stream wall. The membrane can be tar, reinforced concrete, asphaltic concrete, metal, fibre reinforced polymer, clay, secant pile, or geomembrane. Diaphragms are not readily available for inspection or emergency repair when ruptured due to a material flaw or settlement of the dam or its foundation.

2.4 TGSB

TGSB are made of homogeneous fill with slope pitching but can be considered of having two distinct horizontal zones the pure soil zone and the root-soil zone. The root zone is usually 0.5 m below surface and about 2 m thick vertically. It extends 5 to 10 m depending on age of tree horizontally from axis of tree.

3 Design Data

The data required is found out from detailed investigation of foundations and sources of construction materials as per relevant codes [1], [6], [7] and [16]. These are then used for the design of TGSB. These include soil classification and particle size distribution, density, Young's modulus, Poisons ratio, void ratio, Atterbergs limits, and shear parameters. The scope of data required and methodology of obtaining it is governed by the nature of the project, the purpose and the design. The extent of foundation investigations is governed by the geology of the site. The foundation soils' ability to resist the shear stresses imposed by the weight of the embankment and reservoir load must be analysed. The possibility of some silt and clay foundations of low density to be subject to loss of strength during earthquake loading must be investigated and analysed.
The typical soil curve for TGSB is given in Fig. 4 and the typical values used later on for software verification of data are given in Table 1. Soil used in TGSB is typically silty sand sourced from borrow pits nearby.

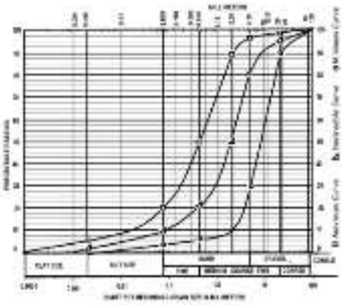

Fig. 4. Particle size curves for Indian standard sieve sizes for soils used in TGSB

Table 1. Values for soil and root zones inputted for Software Verification

Soil	E Mpa	ν	γ_d kN/m^2	γ_{sat} kN/m^2	c kN/m^2	ϕ °
Bund	50	0.33	20	22	11	38
Root & Pitching	100	0.30	15	18	30	40

4 General Construction Methods for TGSB

Traditional construction methods are used for placement in lifts, and equipment used for compaction of the embankment in TGSB. The main material of the bund was dredged sand from river bed. It was stabilized with burnt-shell-lime and coconut leaf which acted as pozzolanic cement. The Plasticizer used was coconut jaggery molasses. Cow-dung and ash also increase cohesion and water tightness while managing the fine contents as the soil was sandy by nature. Layers were laid in lift of 30 to 50 cm with rice straw layers as initial geofabric placed in-between. Facing layer (pitching) was made up of 50 cm thick interlocking coursed dry lateritic rubble masonry. This was placed first before placing soil-lime-ash mix (kaloi). Compaction was done by using initially using coconut tree stump rammer then by a line of 4 to 6 bullocks walking in a line doing 10 passes per layer. Two lines of Coconut trees were planted on either side as a natural geogrid, to reinforce the structure by their fibrous root system (Fig. 5). There was a compacted lateritic cobble (mud) road in the center and vegetation was allowed to grow in the sides. This allowed a natural gradient of 1:100 towards the edge. The topmost rubble of the pitching always projected 30-50 cm above ground level on either side. The side sloped 0.5m for every 3 m height and there were berms (1.5 m on landside/leeward and 0.5 m on riverside/seaward) for every additional 3 m height. Notched bamboo poles of cut size were used to measure and align the TGSB.

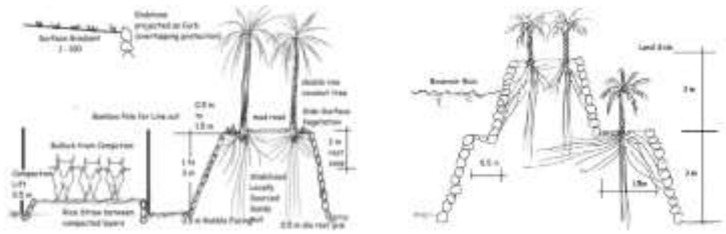

Fig. 5. Construction of Traditional Goan Saraswat Bunds

5 Embankment Details for TGSB

As design is traditional all details are empirical. All measurements for TGSB were done using hand from elbow to finger tip (hatt) and hence were multiple of 0.5m (Fig. 6 & 7)

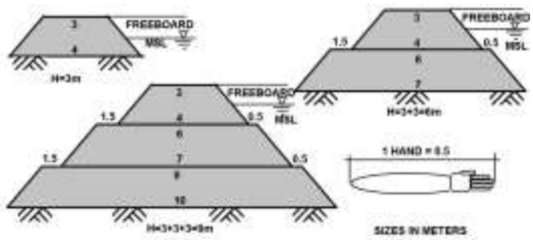

Fig. 6. Typical TGSB with hand as measuring size

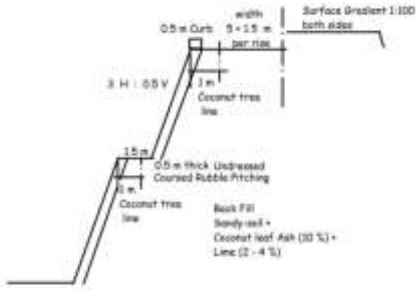

Fig. 7. Typical Dimensions of Traditional Goan Saraswat Bunds

5.1 Crest Width

The crest width (Eq. 1) of TGSB depends on roadway requirements, properties of embankment materials, practicability of construction, planned future extensions, seismicity of area and potential security-related vulnerabilities.

$$C = 5 + 1.5N \quad (1)$$

where C is crest width, N is number of berms/rises.

5.2 Bottom Width

The bottom width of TGSB depend on crest width, properties of embankment materials, practicability of construction, planned future extensions and seismicity of area

$$B = 6 + 4N \quad (2)$$

where B is bottom width, N is number of berms/rises.

5.3 Drainage

Surface drainage of the crest should be provided by a crown with a 1-2-percent slope to the edges or by sloping the crest in both directions. Surface drainage must also be provided on the abutments and valley floor of water retaining TGSB to avoid unsightly gullying at the contact of the embankment with abutments.

5.4 Camber

Camber of 2- 4 percent is provided along the longitudinal axis of the crest of TGSB to ensure that the freeboard will not be diminished by post-construction foundation consolidation and embankment compression. It depends on crest width and materials of foundation and fill.

5.1 Surfacing and Vegetation

Grass or small plant/herb vegetation is to be allowed only on embankment crest to provide protection against damage by wave splash, rainfall runoff, wind, and traffic wear when the crest is used as a public roadway. Two rows of coconut trees places in zigzag manner 10 m center to center are placed on either side of the crest and on land-side berms 1 m from the edge. Under no circumstances must any other tree be planted on the top of a TGSB.

5.2 Overflow Protection

A 0.5 m high curb/kerb wall of dry rubble masonry is provided on both the topmost edges this protects against washout in case of overtopping of embankment and also as public protection from falling off.

5.3 Freeboard

The normal freeboard is fixed as 0.5m for salt pan bunds, 1.5 m for rain water harvesting lakes and 2 m for river-training bunds.

5.4 Slope Protection

The sides of TGSB are sub vertical with 0.5H:3V slope. The side slopes of TGSB are protected against destructive wave action by 0.5 m thick coursed undressed lateritic rubble pitching. On the downstream side provision may be made against burrowing animals (diaphragm or soil-lime concrete may be placed and compacted in horizontal-step layers behind and along with the rubble pitching).

5.5 Abutments

The upstream and downstream slopes of the embankment may be flared at the abutments for stability, and edge seepage control. When vegetation near the abutment contact is removed during construction operations loose soil must also be removed.

5.6 Typical Maximum Sections

Typically TGSB are 1-3 m high. At rain harvesting lakes and canal sides they may extend to 6 m height. Traditional TGSB never exceed 9 m height. As most transportation embankments in India rarely cross 15 m height (higher roads are carried on bridges) TGSB can be used easily. However, for design purpose of TGSB height up to 45 m have been considered in this paper as shown in Table 2 below.

5.7 Foundation

The term foundation includes both the floor and the abutments upon which the embankment will be built. It must stably support the embankment under all conditions of loading and saturation. It must be sufficiently seepage resistance. It must prevent internal erosion and excessive loss of water. Provisions for treatment of the foundation are provided as per codes in designs to meet the essential requirements like excavation of unsatisfactory materials, foundation grouting, material densification, use of filters, and surface treatment measures such as shaping, slush grouting, and dental concrete [9], [12] and [14]. Each foundation has its own unique problem set which require corresponding remedies.

Table 2. Dimensions for design

Berms per side (N)	Bund height(H) m	Crest Width (C) m	Bottom Width (B) m
0	1-3	5	6
1	3-6	6.5	10
2	6-9	8	14
3	9-12	9.5	18
4	12-15	11	22
5	15-18	12.5	26
6	18-21	14	30
7	21-24	15.5	34
8	24-27	17	38
9	27-30	18.5	42
10	30-33	20	46
11	33-36	21.5	50
12	36-39	23	54
13	39-42	24.5	58
14	42-45	26	62

6 Embankment Analysis for TGSB

Essentially, the TGSB must fulfil its required function with adequate safety at a minimum cost in its life time for which it has to undergo rigorous analysis after design prior to construction. The design must give sufficient factor of safety. Material strength properties are governed by the nature of the soil and the drainage conditions. Limit equilibrium based Spencer's procedure is the preferred method of stability analysis of embankments is on. Circular and non-circular shear surface geometries are considered. Typical factor of safety values are given in Table 3.

Table 3. Typical Factor of Safety [6]

Loading conditions	Shear strength parameters	Pore pressure characteristics	Minimum factor of safety
End of construction	Effective	Generation of excess pore pressure with field monitoring	1.3
Steady state seepage	Effective	Steady state seepage in active conservation pool	1.5
Operational conditions	Un-drained	Steady state seepsge under maximum reservoir level	1.2
Other	Effective or Un-drained	Drawdown at maximum outlet capicity	1.2

TGSB must be designed to withstand earthquake loading. The designer must consider liquefiable materials from beneath the embankment. Procedures for investigating seismic stability are given in appropriate Design Standards [5].

7 Validation of Traditional design

There are various FEM based software available in the market that can realistically model and analyse various geotechnical structures. Three available software (OptunG2, GEOSTUDIO and MIDAS) were used to validate the design of TGSB.

7.1 Slope Stability for plain embankments of various heights

The stability of TGSB for slope stability was modeled using OPTUM-G2 software using Limit analysis and strength reduction analysis (Fig. 8).

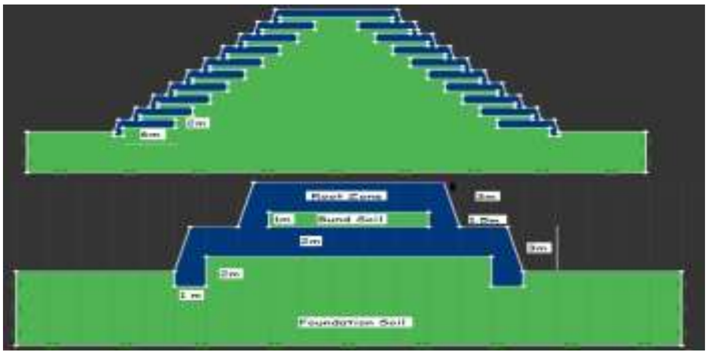

Fig. 8 TGSB model in OptumG2 for 6m and 30 m Heights

The embankments were tested for heights varying from 3 to 45 m. the model used soil and root zone properties shown in Table 1. Bund and foundation soil were considered for same value. There was good factor of safety of more than 1.2 available up to 24 m height (Table 4 & Fig. 9). The factor of safety shows an initial sharp fall with increase in height, but it levels out after 12 to 15 m. There were zero displacements in x-x and y-y directions up to 12 m height (Table 5 & Fig. 10). Stresses and strains were also reasonably low for lower heights.

Table 4. Factor of Safety for different bund heights using OptumG2 Software

Bund	Limit Analysis			Strength Reduction Analysis		
Height	Lower	Upper	Average	Lower	Upper	Average
3	6.166	10.934	8.550 ± 2.384	2.766	3.625	3.1955 ± 0.4295
6	4.732	8.473	6.6025 ± 1.8705	2.070	2.438	2.254 ± 0.184
9	3.584	6.634	5.109 ± 1.525	1.751	2.031	1.891 ± 0.140
12	3.136	5.368	4.252 ± 1.116	1.555	1.719	1.637 ± 0.082
15	2.482	4.199	3.3405 ± 0.8585	1.384	1.547	1.4655 ± 0.815

24	1.843	2.779	2.311 ± 0.468	1.154	1.270	1.212 ± 0.058
30	0.955	1.380	1.1675 ± 0.2125	0.986	1.078	1.032 ± 0.046
45	0.507	0.675	0.6225 ± 0.0525	0.848	0.914	0.881 ± 0.033

Table 5. Stress and displacement at toe for different dam heights using OptumG2 Software

Bund Height	Stresses kN/m^2 σ_{xx}	σ_{yy}	Displacements m u_{xx}	u_{yy}	strains ε_{xx}	ε_{yy}
3	-52	-32	0.000	0.000	4.250	0.008
6	-58	-52	0.000	0.000	0.280	0.010
9	-61	-78	0.000	0.000	0.250	0.020
12	-67	-89	0.000	0.000	0.020	0.030
15	-72	-110	0.035	0.058	0.020	0.040
24	-114	-127	0.300	0.089	0.018	0.090
30	-127	-164	0.381	0.100	0.018	0.130
45	-164	-233	0.420	0.150	0.015	0.120

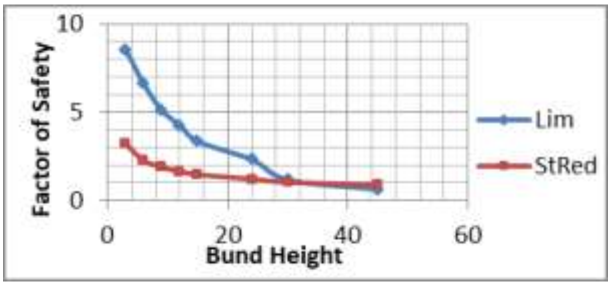

Fig. 9. Factor of Safety for different Bund Heights in OptumG2

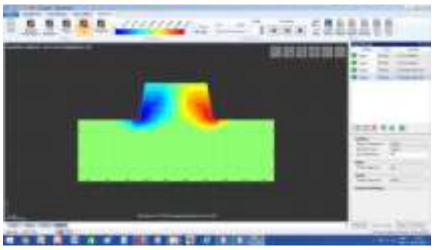

Fig. 10. Stress distribution for 3m Bund Heights in OptumG2

7.2 Slope stability for water retaining embankments

The stability of TGSB for retaining water was modeled using GEOSTUDIO SLOPE 7, using Morgenstern Price method for slope stability for leeward side and seaward side for 3,6, 9 m bunds considering a freeboard of 1.5 m on the water retaining side (Fig. 11). The least factor of safety was found to be 1.52 and well within safe limits (Table 6).

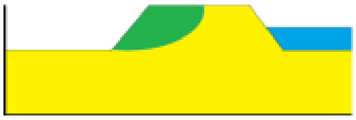

Fig. 11. Slip circle for 3m Bund in GEOSTUDIO SLOPE

Table 6 Factor of safety of slope using GEOSTUDIO SLOPE [15]

	Factor of safety of slope		
Depth	3 m	6 m	9 m
Leeward side	2.78	1.74	1.52
Seaward side	4.87	2.41	2.33

7.3 Seismic Slope stability

The dynamic slope stability contribution of roots was studied by considering the stability of slope for 3, 6 and 9 m heights with and without roots. MIDAS-GTS-NX software was used for the analysis (Fig. 12). They were subjected to an earthquake of M5 magnitude with 0.2g acceleration. The results for bunds reinforced with root mat and root piles showed almost zero displacements and zero additional stress during earthquake. This was due to the damping by roots. The minimum factor of safety was 1.46 was well within limits (Table 7).

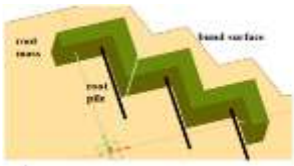

Fig. 12. Root mass and root pile for 9m Bund in MIDAS-GTS-NX

Table 7. Factor of safety of slope for Seismic Stability using MIDAS GTSNX

	Factor of safety of slope		
Depth	3 m	6 m	9 m
Without Roots	2.98	1.78	1.46
With Roots	4.53	2.46	1.98
Difference	1.55	0.67	0.52
% Increase	34.2	27.3	26.2

8 Conclusions

Traditional Goan Saraswat Bunds have been around for millennia. They are truly sustainable structures of maximum 9 m height. Their design involves simple thumb rules. They are multipurpose bermed embankments with coconut trees on top. The design was validated using three different softwares. They were found to be extremely safe for small height embankments and low embankment dams. They can withstand low magnitude earthquakes very effectively due to the damping by their roots. However, more studies need to be done with regard to permeability and seepage analysis.

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