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Stability Analysis of Tailings Dam Using Finite Element Approach and Conventional Limit Equilibrium Approach

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Abstract. The probability of failure in tailings dam is generally found to be much greater than the conventional water retaining dams. Slope instability is one of the major reasons, contributing more often to the failure of these tailings dam. Due to this reason, the stability of tailings dam has drawn much attention as significant numbers of tailings dam's failure havebeen reported worldwide in the recent years. The present work focuses on evaluating the stability of existing tailings dam by using finite element method (FEM) as well as conventional limit equilibrium methods (LEMs) under static loading conditions. Shear strength reduction (SSR) technique is incorporated (by using 2D finite-element based package RS^2)in order to observe the potential modes of failure. Further, Rocscience SLIDE-2D is utilised to evaluate the stability of dam embankments by LEM. The results obtained from the analysis utilizing both LEM and FEM are compared in terms of their global factor of safety (FOS) and strength reduction factor (SRF) respectively. Further, an attempt is made to explore the stability of different types of tailings dam, based on their method of construction (i.e. upstream (U/S) method and downstream (D/S) method). The results obtained from LEM and FEM are found be in good agreement with each other. It is observed that the FOS and SRF values decrease as the height of embankment is raised. In addition, the failure surface is found to be circular in FEM for most of the critical slopes, which supports the assumptions of circular slip surface consideredin LEMs based analysis. In addition, D/S slope is found to be more susceptible to failure than the U/S slope, for both U/S and D/S methods of construction.

Keywords: Tailings dam, stability analysis, factor of safety, FEM, LEM.

1 Introduction

The demand of mineral products has increased substantially in the recent years due to rise in economic development resulting in the production of significant volume of tailings.'Tailings' are the left over waste generated by the mining industries during the extraction of metals (Fe,Ni,Mn,Au etc.), minerals (diamond, gypsum, asbestos etc.) or mineral fuels (coal etc.) from their respective ores. These tailings generally are fine grained crushed rocks having size predominately ranging from sandy to silty (EPA, 1994). The ratio of concentrate mineral to tailings is generally considered approximately around 1:200 (Lottermoser, 2007). Hence, mining operations discharge huge volume of tailings which needs to be disposed-off effectively. Different types of approaches such as riverine disposal, submarine disposal, backfilling, dry stacking and storage behind dammed impoundments, are used to dispose the tailings waste (Lottermoser, 2007). In order to avoid formation of surface dust (due to oxidation) and acid mine drainage, tailings are mostly stored behindwater holdingdams (more often called as "tailings dam") (Kossoff et al. 2014).

Construction of tailings dam is a continuous process where dam embankments are raised depending upon the volume of tailings waste being generatedby the mining operations. By doing so, the initial cost of construction is reduced considerably. The materials used for the construction of embankments can be either borrowed (generally obtained from the impoundment area) or from the tailings itself (EPA, 1994). In most cases, tailings are more often used for constructing the embankments subjected to meeting the permeability, compressibility and shear strength requirements of embankments (EPA, 1994). However, use of tailings as a construction material makes the tailings dam susceptible to liquefaction, internal piping and highly erodible surfaces (Vick, 1990). Based on the relative position of crest, there are three methods which are used to constructa tailings dam i.e. U/S method (see Fig. 1), D/S method (see Fig. 2) and centreline method (see Fig. 3) (Vick, 1990).

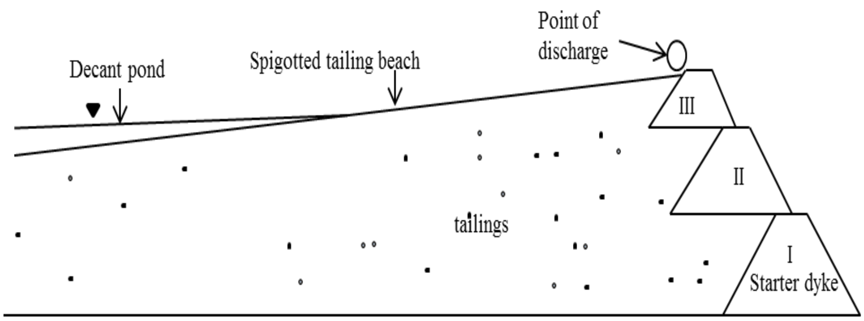

Fig. 1.U/S method of tailings dam construction (recreated after Vick, 1990)

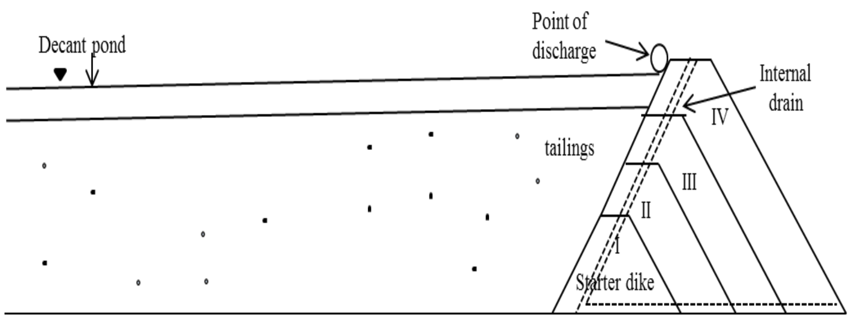

Fig. 2. D/S method of tailings dam construction (recreated after Vick, 1990)

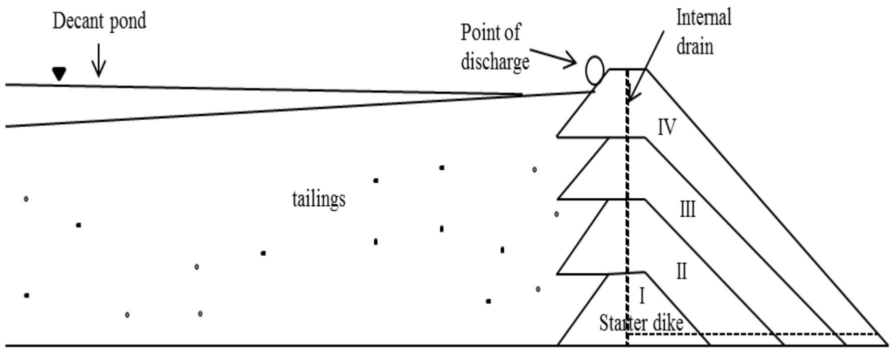

Fig. 3. Centreline method of tailings dam construction (recreated after Vick, 1990)

The probability of failure in tailings dams is generally found to be much greater than the conventional water retention dams. The rate of failure, in case of tailings dams, is found to vary between 1 in 700 to 1 in 1750 as compared to 1 in 10000(approximately) for water retention dams (Davies, 2001). Further, the rate of failure is found much higher (83%) for active tailings dams as compared to inactive ones (15%) (Rico et al. 2008). The causes of tailings dam failure can be broadly categorised into foundation failure, slope instability, liquefaction, overtopping, piping or seepage, structural and others (snow melt, mine subsidence etc.) (Rico et al. 2008).Moreover, it is also observed that 66% of failures occurred in those tailings dams which were built using U/S construction technique (Sitharam and Hegde, 2017). Further, it is observed from the existing literature that the slope instability is one of the major causes, contributing more often to the failure of thetailings dams. Due to this reason, the stability of tailings dams has drawn much attention as significant numbers of tailings dam's failure had been reported worldwide in the recent years.

The present work focuses on evaluating the slope stability of existing tailings damby using FEM as well as conventional LEMs under static loading conditions. SSR technique has been incorporated (by using 2D finite-element based package RS^2)in order to find out the potential modes of failure whereasRocscience SLIDE -2D has been utilised to evaluate the stability of tailings dam based onLEM. The results obtained from the analyses utilizing both FEM and LEM are compared in terms of their global FOS and SRF. Further, an attempt has been made to explore the stability of different types of tailings dams, based on their method of construction (i.e. U/S method and D/S method).

2 Site Description

The data for the present stability analyses is taken from Sitharam and Hegde (2017) related to an existed tailings dam. The reported tailings dam is situated in Rampura Agucha Mine (RAM) in Rajasthan, India (see Fig. 4). The primary product being extracted from the mine is Zinc whereas it generateslead as secondary product (Sitharam and Hegde, 2017). Plan area of tailings pond is approximately 1200m x

800m. Fig. 5 shows the dimensions of already existingtailings dam, the height of which was required to be raised from 27m to 51m (Sitharam and Hegde, 2017). The tailings dam has U/S slope of 2H: 1V whereas D/S slope angle was considered as 36^0. The top width of tailings dam (crest width) was provided as 30m.

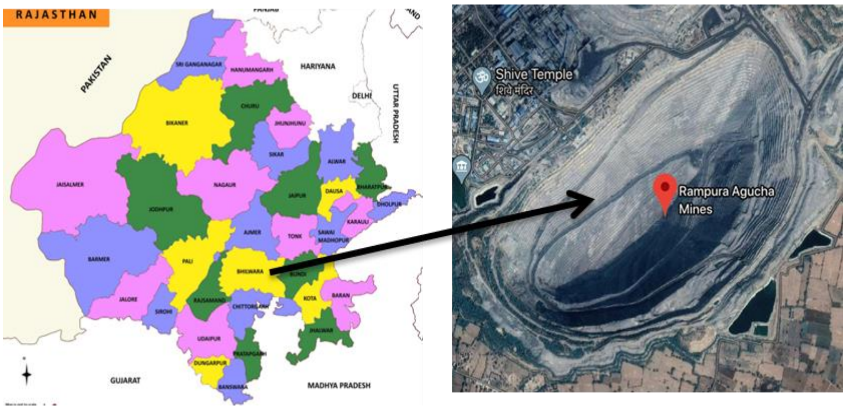

Fig. 4. RAM location (Google maps, accessed on 15[th]july 2020)

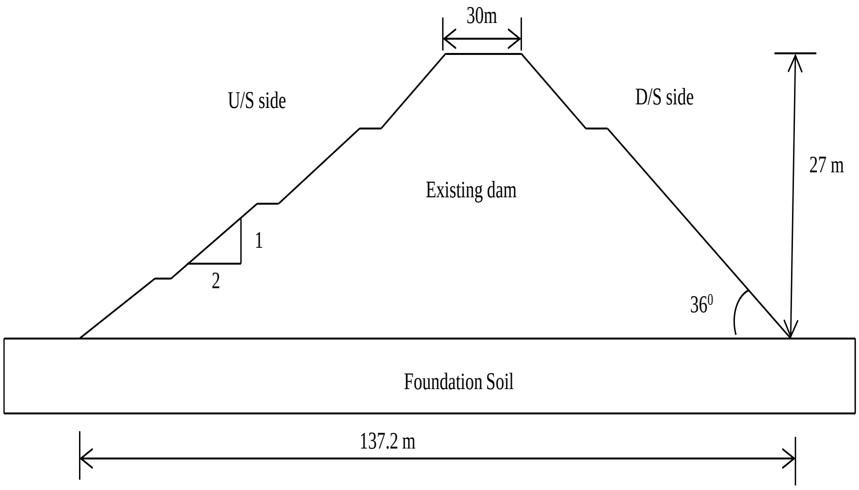

Fig. 5. Typical cross-section of RAM tailingsdam used for the analysis (Sitharam and Hegde, 2017)

3 Foundation Soil and Tailings Properties

The RAMtailings dam was built over low permeability soil (0.8 x 10^{-8} to 1 x 10^{-8}m/s), which was underlain by rocky strata. Table. 1 presents various properties of foundation soil and tailings used in the present work. Embankments were built using mine spoil which is crushed rock waste produced during mining operations.

Table 1. Properties of materials used for the study (Sitharam and Hegde, 2017)

Properties	Foundation soil	Mine spoil	Settled mine tailings
Bulk unit weight, *γ* (kN/m3)	22	20.7	20
Cohesion, *c* (kN/m2)	20	2	1
Friction angle, *φ* (°)	38	39	35
Bulk modulus, *K* (MPa)	40	20	10
Shear modulus, *G* (MPa)	20	10	5

4 Construction of Dam Embankments

It should be noted that a dam already exists of 27m height and in this work, the stability of dam is analysed against rise of embankment. Such rise of embankments can be done by adopting U/S method,D/S method and centreline method of construction. In the present wok however, only D/S and U/S methodsareconsidered as most of the existing tailings dams are constructed using these methods. In D/S method, dam embankments are raised by shifting the centreline of crest towards D/S side of tailings dam (see Fig. 6).In U/S method of construction, the height of dam embankment is raised in such a way that the centreline of crest moves towards the U/S side of tailing dam (see Fig. 7). Thus, the foundations of subsequent embankments in the U/S approach will rest over the already deposited tailings. For the present analysis, construction of tailings dam in each method is allowed to complete in 4 phases. In each phase, the height of embankments is raised by 6m. In addition, the D/S slope, U/S slope and the crest width in each phase are kept same as that of already existing dam. Further, stability analyses are using LEM and FEM are performed as discussed in the further section.

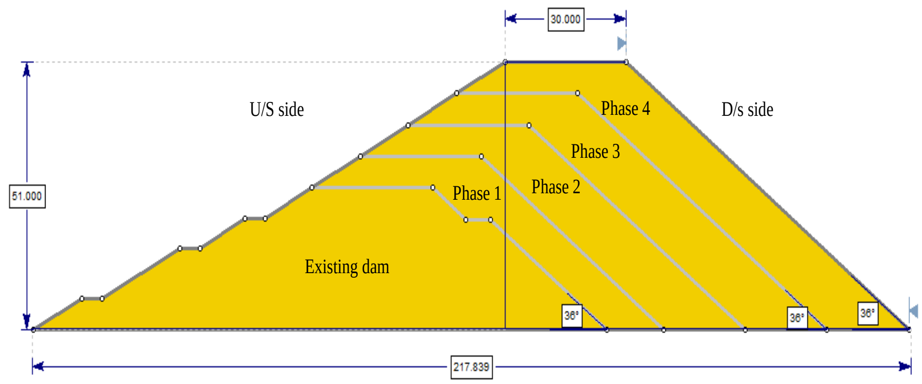

Fig.6. A typical cross-section of tailings dam at the end of construction using D/S method of construction.

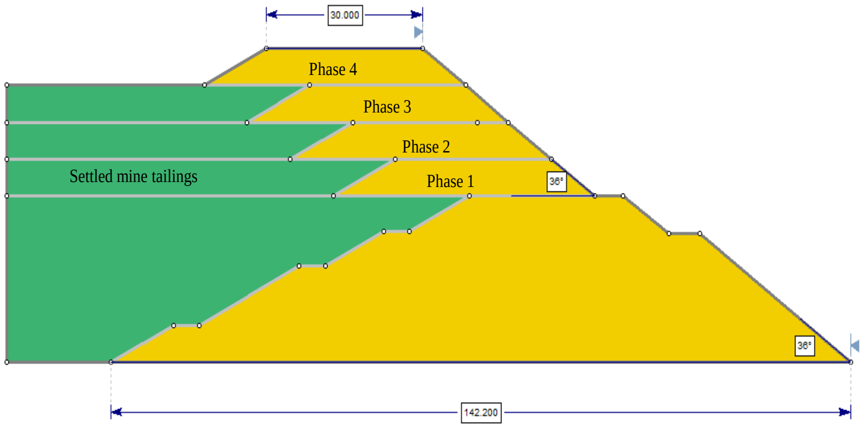

Fig. 7. A typical cross-section of tailings dam at the end of construction using U/S method of construction.

5 Stability Analysis Using LEM

In general, the stability of dams isassessed for three cases i.e. at theend of construction, sudden drawdown and steady seepage. The concerned tailings dam is analysed only for the 'end of construction (only for static loading)' case as the other two cases hold negligible importance for the present tailings dam (due to material properties) (as highlighted by Sitharam and Hegde, 2017).SLIDE-2D by Rocscience is utilised in the present study, which performs the stability analysis by incorporating different LEM methods. Further, Bishop's method (Bishop, 1955), Janbu's simplified method (Janbu, 1973), Spencer's method (Spencer, 1967) and Morgenstern- Price method (Morgenstern and Price, 1965) are used to perform the stability of embankment slopes. Only circular slip surface is assumed for each method as the embankment material is homogeneous in nature. Moreover, slopes having slope angle >30^0(36^0 in present case) has been mostly observed to have circular failure surface (Salmasi et al. 2019).Stability analysis (for bothU/S and D/S case) is performed after completion of each phase of construction.

5.1 Results and discussion

Obtained results of stability analysis during different phases of constructionand using D/S method, aresummarized in Table 2. It can be observed from Table 2 that the FOSvalue decreases as the height of tailings dam increases. However, FOS can be kept unchanged by providing suitable berm width at the end of each phase and thus maintaining the constant height of embankment (Sitharam and Hegde, 2017). By doing so, the overall area occupied by dam will increase thus increasing the material required for the construction of embankments. Further, it was observed from Table 2 that choice of different slope stability methods have negligible effect on the obtained FOS in all phases of construction.Fig. 8 shows the FOS obtained for D/S slope at the end of phase 4 constructed by D/S method of construction following Bishop's method.

Table 2. FOS for D/S slope observed during different stages of construction using D/S method

Stages of Construction	FOS based on			
	Bishop's Method	Janbu's Method	Spencer's Method	Morgenstern-Price Method
Phase 1	1.228	1.204	1.223	1.224
Phase 2	1.220	1.195	1.216	1.216
Phase 3	1.210	1.188	1.205	1.206
Phase 4	1.201	1.183	1.197	1.197

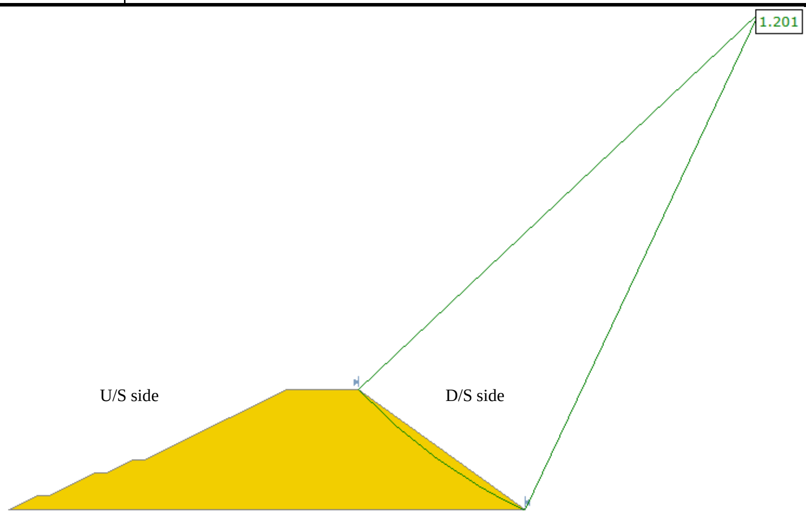

Fig. 8.A typical stability analysis result of D/S slope constructed byD/S method of construction.

In case tailings dam is constructed using U/S method of construction, U/S slope might behave as a critical slope. This is due to the reason thatin case of U/S method, the foundation of subsequent embankments directly rests over the tailingsstored in the previous embankments (see Fig. 9). Hence, rate of raising the embankment is an important factor while raising the embankment using U/S method of construction. Moreover, in comparison to D/S method of construction, U/S method can have both U/S and D/S slopes as critical. Therefore, in order to make the outcomes of analysis more reliable, FOS in the present work is calculated for both U/S slope (see Fig. 9) as well as for D/S slope (see Fig. 10). Obtained results based on the analysis, for each phase of construction and following different stability analyses methods are summarized in Table 3 and Table 4 for D/S and U/S slope respectively. From the table 3, the trend in the FOS is observed to be same as it was observed in case of D/S method.It can be observed from the Table 4 that the FOS is same for the U/S slope during all phases of construction. This is due to the fact that the slope geometry used for the construction of U/S slope was kept same in allphases of construction.

Comparing the outcomes based on both methods of construction, it can be noticed that the FOS for the embankments constructed by D/S method is less as compared to embankment constructed by U/S method. This is due to the reason that in case of D/S method, the entire D/S slope behaves as a critical slope (see Fig. 8) whereas for U/S method,only a part of D/S slope is found to be critical (see Fig. 10). However, as discussed earlier, this value of FOS can be increased for D/S slope by providing a berm of suitable width (as shown in Fig. 8), which will reduce the slope height and hence will increase the FOS (Sitharam and Hegde, 2017) of D/S slope.

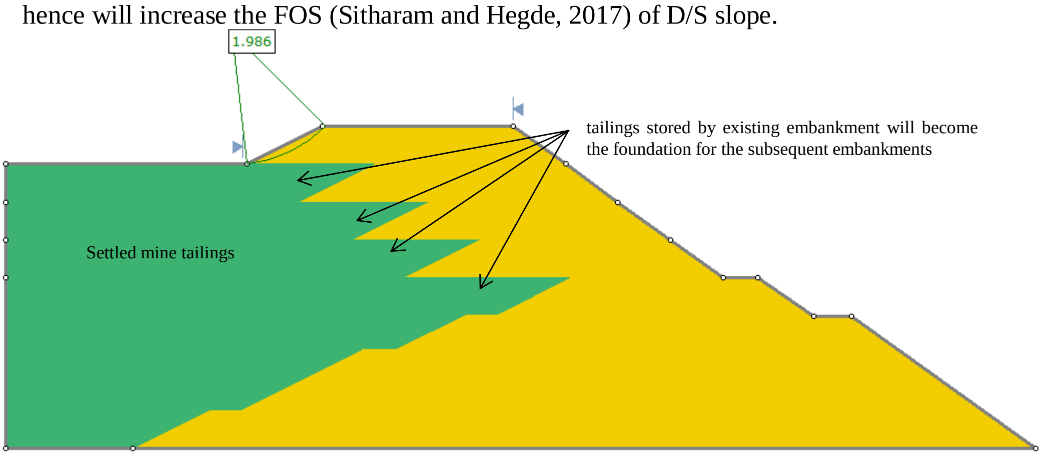

Fig. 9. A typical stability analysis result of U/S slope constructed using U/S method of construction.

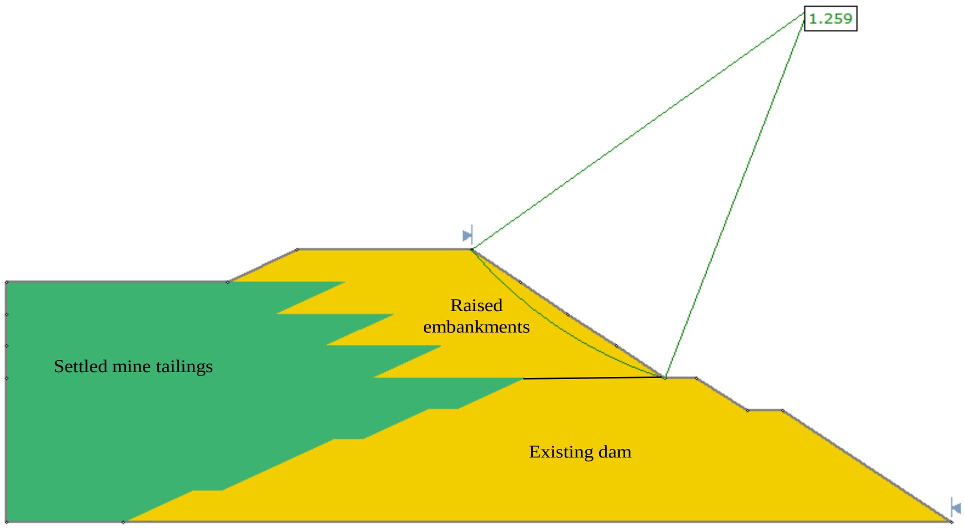

Fig. 10. A typical stability analysis result of D/S slope constructed using D/S method of construction

Table 3. FOS for D/S slope observed during different stages of construction using U/S method

Stages of Construction	FOS based on			
	Bishop's Method	Janbu's Method	Spencer's Method	Morgenstern-Price Method
Phase 1	1.267	1.236	1.265	1.263
Phase 2	1.267	1.236	1.265	1.263
Phase 3	1.267	1.236	1.265	1.263
Phase 4	1.259	1.230	1.253	1.255

Table 4. FOS for U/S slope observed during different stages of construction using U/S method

Stages of Construction	FOS based on			
	Bishop's Method	Janbu's Method	Spencer's Method	Morgenstern-Price Method
All Phases (i.e. for phase 1, phase 2, phase 3 and phase 4)	1.986	1.870	1.986	1.986

6 Stability Analysis Using FEM

Although, LEM used in previous section is simple to perform but it has certain limitations. Firstly, the technique does not consider the stress-strain behaviour of materials while calculating the FOS values. Secondly, in order to ensure the static determinacy, LEM uses arbitrary assumptions regarding the inter-slice forces. Therefore, to avoid the inaccuracy caused due to inherent drawbacks of LEM, FEM has been used more frequently in the recent years. In the present work, another set of analyses is done using RS^2 by Rocscience,which performs analysis usingFEM approach.SSR technique is used to assess the stability of slopes where shear strength of a material is reduced (by reducing shear strength parameters i.e. cohesion and angle of internal friction) in each stage, until the slope fails completely. Further, Mohr-Coulomb model is adopted to simulate the behaviour of both foundation soil as well as embankment material (mine spoil). Bottom boundaries are restrained in both vertical and horizontal direction whereas side boundaries are restrained in horizontal direction only. These boundary conditions represent the slope stability problem in a better way. At the bottom boundary there will be hardly any displacement in x and y-directions due to confinement from all the directions. Similarly, along the side boundaries, soil will be less confined in y-direction due to low overburden pressure and thus the soil particles can be allowed to displace vertically.Further, referring to Table 1, all material properties are assigned.

6.1 Results and discussion

The accuracy of results obtained based onFEM depends upon various factors such as boundary conditions, mesh fineness, mesh gradation, mesh shape etc. Therefore, optimum values of these parameters are found initially and then those values are used in the analysis. The results obtained by the FEA of the tailings dam developed using U/S method and D/S method of construction is shown in table. 5. The variation of SRF (analogous to FOS in LEM) with height is found to be similar to FOS as observed in case of LEM. SRF is observed to decrease with increase in the height of embankment. Even in FEM based analysis, the D/S slope is found critical for both the cases (i.e. for U/S method of construction and D/S method of construction) as can be observed from Fig. 11 and Fig. 12 respectively. Further, the failure surface for critical slopes is observed to be approximately circular (see Fig. 12) which is in agreement with the assumption made in the LEM based analysis carried out in previous section.

Table 5. Strength reduction factor (SRF) obtained for tailings dam during different stages of construction

Stages of construction	SRF	
	U/S method	D/S method
Phase 1	1.28	1.20
Phase 2	1.27	1.19
Phase 3	1.25	1.17
Phase 4	1.24	1.15

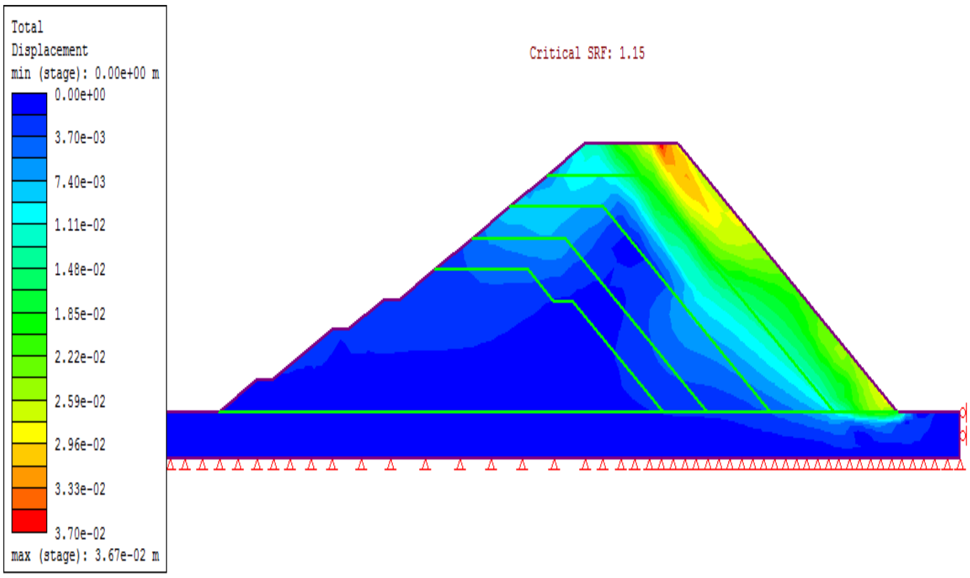

Fig. 11. SRF observed at the end of phase 4 construction using D/S method of construction

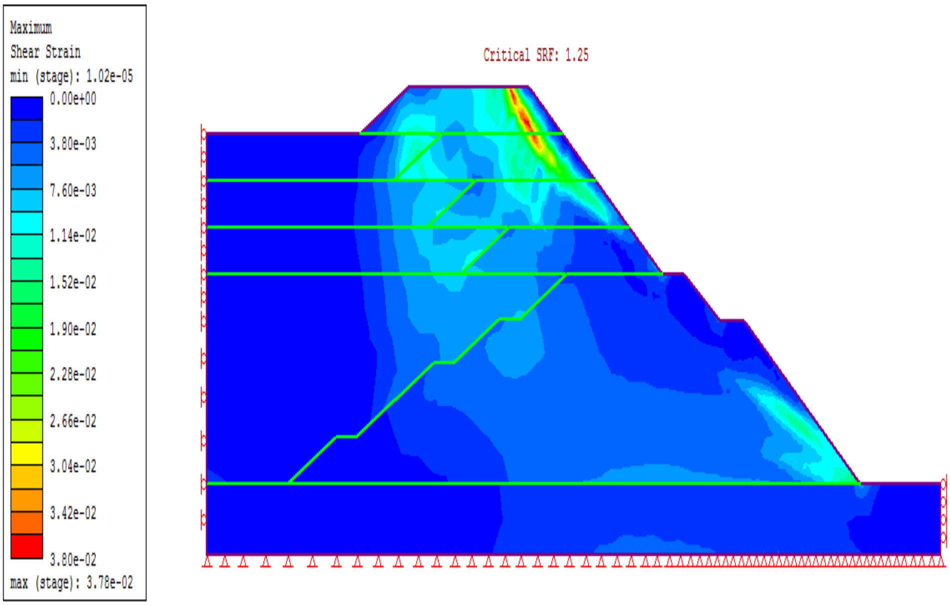

Fig. 12. SRF observed at the end of phase 4 construction using D/S method of construction

7 Comparison of Results Obtained from Lem And Fem.

Previous sections highlighted the results obtained from stability analysis performed using LEM and FEM. Figs. 13 and 14 show the comparison between the results obtained from FEM and LEM for both methods of construction. It can be noticedfrom Fig. 13that the results obtained from FEM is a bit conservative as compared to the results obtained from LEM for the slope constructed using U/S method of construction. However, the difference between the SRF and FOS values is very less, which makes the stability analysis and hence the design quite reliable. Further, it can be also observed from Fig. 14 that FOS from Janbu's method shows least value of FOS in comparison to other slope stability methods is U/S method of construction. Further, except for Janbu's method, FEM gives lesser SRF values at large heights (>42m) in comparison to other LEMs. Overall, FEM gives a bit conservative results as compared to LEMs.

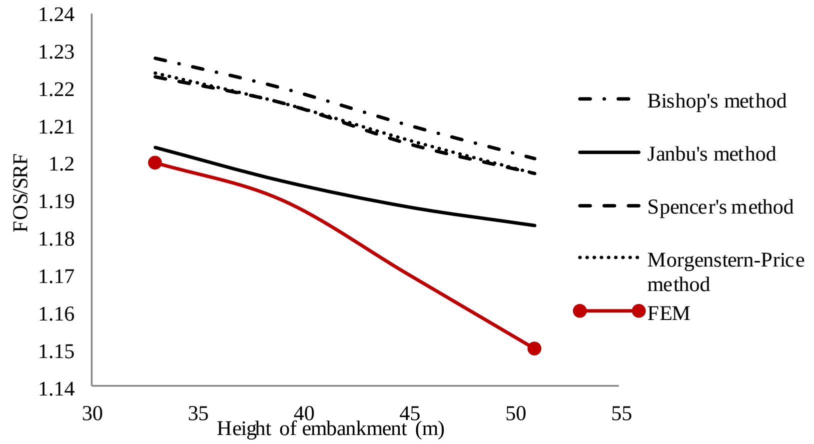

Fig. 13. Comparison of results obtained from LEMand FEM for D/S slope constructed using D/S method of construction

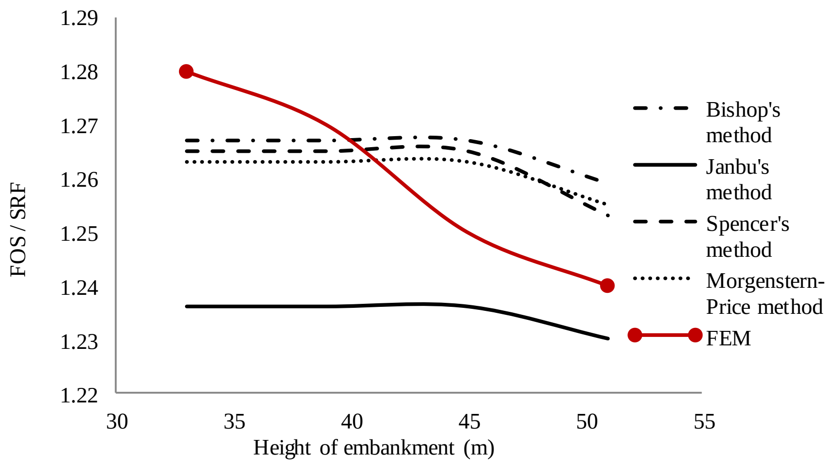

Fig. 14. Comparison of results obtained from LEMand FEM for D/S slope constructed using U/S method of construction

8 Conclusions

The current work attempts the stability analysis (static loading only) for RAM tailings dam located in Rajasthan, India, the height of which was planned to be raised from 27m to 51m. The two widely used method of construction i.e. U/S method and D/S methodare adopted to raise the tailings dam. The stability analysis of the embankments is initially performed in SLIDE-2D program which is based on LEM.

Bishop's method, Janbu's method, Spencer's method and Morgenstern-price methods of slope stability are used to perform the stability analysis. In addition, FEM is incorporated further to carry out the slope stability analysis. The FEM based analyses is carried out by using RS^2 program which uses SSR technique to perform the analysis. Results obtained from both the methods are then compared in order to make the outcome of slope stability analysis more reliable. Results obtained from LEM and FEM are found in good agreement with each other. Further, it is observed that the FOS and SRF values decreases as the height of embankment is raised. In addition, the failure surface is found to be circular in FEM for most of the critical slopes which support the assumptions of circular slip surface in LEMs. Moreover, the critical slope liable to failure is found to be D/S slope for the embankments either built by U/S method of construction or by D/S method of construction. In general, the results obtained from the FEM are found to be a bit conservative as compared to the results obtained by utilising limit equilibrium approach.

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