DYNAMIC ANALYSIS FOR LAKYA IRON ORE TAILINGS DAM
AT KUDREMUKH, KARNATAKA

R. P. Gupta¹, B. Muralidhar²

ABSTRACT

Benefaction process for the production of iron ore concentrate generates tailings as a waste material that needs to be safely disposed. The iron tailings of 7.5 million tonnes generated annually by Kudremukh Iron Ore Company Ltd (KIOCL), Karnataka, had been disposed in a lake created by 103.0m high and about 1.0 km long Lakya earthen dam. In two decades period, 80% of the lake capacity had been utilized and balance capacity would be consumed in next 4 – 5 years. Future disposal of tailings demanded an increase of storage capacity by raising the height of the dam by 15.0 m. It was proposed to increase the height by constructing 5 dykes of 3.0 m high each, using tailings materials, by upstream method of construction. The dynamic stability of the proposed dykes resting on loose tailings deposit was checked, since tailings deposits are susceptible to liquefaction type of failure during earthquake.

Tailings are fine grained, poorly graded non-plastic silty sand (SM-SP) having specific gravity of 2.8. Tailings are transported in slurry form through pipelines and discharged into the reservoir near the dam. Standard Penetration Test (SPT) carried out in the tailings deposit indicated penetration resistance values of 0 up to a depth of 4.0 m from top which gradually increased to 5 blows/foot at 10.0m depth. The average dry density of tailing deposit is 1450 kg/m³ while that of compacted tailings is 1780 kg/m³. Non-linear soil strength parameters were evaluated for loose as well as compacted tailings material and earth dam soil. Strain dependent dynamic shear modulus and damping ratio properties were determined for tailings materials using Resonant Column tests. Cyclic Triaxial Shear test results of tailings material showed that the generation pore pressure due to cyclic loads was limited to 10% of that required for liquefaction. However, deformation of the tailings sample due to cyclic loads was more than 5%. This indicated that failure in loose tailings deposit may be due to development of excessive strain rather than due to liquefaction. The Cyclic Stress Ratio (CSR) was evaluated as 0.46 and 0.32 for the loose and compacted tailings materials, at equivalent number of loading cycles of 14. The site is located in zone III as per seismicity zones of India. The peak ground accelerations of the site specific Design Basis Earthquake (DBE) are 0.08g and 0.05g in horizontal and vertical directions respectively. Dynamic seismic response analysis

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using Finite element method indicated that maximum induced acceleration of 0.09g. Comparison of ‘shear stresses induced in the tailings deposit and dyke’ with that of its strength indicated that tailings near the toe of dyke would undergo excessive strain leading settlement of the dykes. This would result in overtopping of loose tailings. In order to avoid excessive settlement of the dykes, densification of loose tailings deposit suitable method such as vibro-floatation, vibro-blasting, heavy tamping etc were recommended. It was recommended that the tailings deposit after densification should have minimum penetration resistance value of 15 blows /foot in the top 5.0 m, to ensure stability of the tailings dyke during earthquake.

Keywords: Tailings dam, Dynamic response analysis, Resonant column test
ABSTRACT: Kudremukh iron ore company limited (KIOCL) had been disposing iron ore tailings in a lake created by 103 m high Lakya earthen dam for two decades. Height of the dam was proposed to be raised by 15 m by constructing dykes on loose tailings deposit to cater future requirements. Earthquake stability of the dyke was evaluated, considering the low penetration resistance values of tailings deposit. Laboratory tests were carried out on the soil of earth dam and tailings materials to determine strength parameters, dynamic elastic properties and cyclic strength. The finite element dynamic analysis indicated that the failure of the tailings deposits and dyke would be predominantly by excessive settlement rather than by liquefaction. Strength improvement methods on tailings deposit would be necessary to improve the seismic stability of the dyke.

INTRODUCTION

A number of mine tailing dams have suffered severe damages as result of liquefaction and excessive deformations during past earthquakes. It is reported that 17% failures of tailing dams are due to earthquakes.[1] The most notable example are the Mochikoshi dam, Japan and San Fernando, USA. [2]

An earthen dam of 103 m high was constructed by Kudremukh Iron Ore Company Ltd, Karnataka for the purpose of disposing the iron tailings. It is located in peninsular shield of India, which is characterized by a complex structure with numerous faults, fractures and weak zone. The latitude and the longitude of the site is 13.22° N and 75.23° E respectively and it falls in seismic zone III.[3,4]. In two decades period of mining operation, 80% of the lake capacity had been utilized. Keeping in view the future requirements, it was proposed to increase the storage capacity of lake by constructing 15 m high dyke on tailings deposit, as shown in Fig.1. The proposed dyke would be constructed in 5 stages of 3 m high, using the abundantly available tailings materials. This paper describes field and laboratory test carried out, methodology adopted for assessment of liquefaction susceptibility and dynamic stability of the dyke.

FIELD INVESTIGATIONS

Four bore holes, using rotary wash boring, were drilled: one in earthen dam and three in tailings deposit. The tailings and soil samples were collected at 3.0 m interval open tube sampler of 55mm diameter and 45 cm length. The Standard Penetration Test (SPT) results are given Table 1:

<table>
<thead>
<tr>
<th>Depth from GL m</th>
<th>BH-2</th>
<th>BH-3</th>
<th>BH-4</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.45-3.9</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>6.45-6.8</td>
<td>0</td>
<td>5</td>
<td>18</td>
</tr>
<tr>
<td>9.45-9.9</td>
<td>23</td>
<td>5</td>
<td>9</td>
</tr>
</tbody>
</table>
LABORATORY TESTS

Particle size gradation test indicated that the soil of earthen dam was classified as ‘Well graded silty sand’ (SM-SW) while tailings materials as ‘Poorly graded silty sand’ (SM-SP). It is seen that the gradation of tailings materials lie within the range of potentially liquefiable soils (Fig 2.). Results of Proctor compaction tests showed that the Maximum Dry Density (MDD) of 1.6 and 1.78 gm/cc with corresponding Optimum Moisture Content (OMC) of 18.0 and 14.0%, for soil of earthen dam and tailings materials respectively.

Consolidated Undrained triaxial tests were conducted on soil samples of earthen dam and tailings materials – in loose as well as in compacted conditions. All the tests were conducted with full saturation achieved by Back pressure method. The soil properties are given in Table 2.

![Image](51x390 to 267x491)

**Fig 2.** Particle Size Distribution of tailings

--- Range of potentially liquefiable soils

**Table 2 :** Non-linear shear strength parameters used in the Stability analysis

<table>
<thead>
<tr>
<th>Soil Parameter</th>
<th>Symbol</th>
<th>Unit weight</th>
<th>Modulus number</th>
<th>Modulus exponent</th>
<th>Unloaded-Reloaded modulus</th>
<th>Failure Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grain Size , mm</td>
<td>% Passing</td>
<td>T/cum</td>
<td>K</td>
<td>n</td>
<td>Kur</td>
<td>RF</td>
</tr>
<tr>
<td>A</td>
<td>2.0</td>
<td>102</td>
<td>0.6</td>
<td>122</td>
<td>0.55</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>1.73</td>
<td>60</td>
<td>0.8</td>
<td>180</td>
<td>0.70</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>2.0</td>
<td>238</td>
<td>0.6</td>
<td>346</td>
<td>0.70</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Bulk modulus</th>
<th>( K_0 )</th>
<th>100</th>
<th>50</th>
<th>286</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bulk Exponent</td>
<td>( m )</td>
<td>0.44</td>
<td>0.00</td>
<td>0.44</td>
</tr>
<tr>
<td>Cohesion</td>
<td>( c, t/sqm )</td>
<td>2.0</td>
<td>0.0</td>
<td>2.0</td>
</tr>
<tr>
<td>Friction angle</td>
<td>( \Phi )</td>
<td>33</td>
<td>15</td>
<td>32</td>
</tr>
<tr>
<td>Damping ratio</td>
<td>( D )</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Coeff</td>
<td>( k_0 )</td>
<td>0.46</td>
<td>0.74</td>
<td>0.47</td>
</tr>
</tbody>
</table>

Resonant Column Test

Shear Modulus (G) and Damping Ratio (D), were determined in the laboratory, using the Resonant Column test equipment. In this test, the top end of the cylindrical soil specimen (38 mm diameter x 76 mm high) is vibrated in torsional mode while the other end of the specimen fixed to the pedestal. Test is conducted to determine Resonant frequency (\( f_r \)) of the soil. Shear modulus is computed from equation (1) and (2).

\[
\frac{I_S}{I_D} = \left(\frac{2\pi f_s L}{V_s}\right) \cdot \tan\left(\frac{2\pi f_s L}{V_s}\right) \tag{1}
\]

\[
G = \rho V_s^2 \tag{2}
\]

Where \( I_S \), \( I_D \) are moment of Inertia of soil column and Driver, \( f_r = \) resonant frequency, \( L = \) length of the specimen, \( V_s = \) shear wave velocity. The test is conducted in the shear strain (\( \gamma \)) range of \( 10^{-4} \) to 1.0 %. The \( G_{max} \) is the maximum Shear Modulus value of the soil at the lowest strain (i.e \( 10^{-4} \%) \). Figure 3 gives the variation of noramlised modulus (\( G/G_{max} \)) with that of shear strain.

Damping ratio (D) is computed from the decay curve, which is obtained as a trace in a storage oscilloscope when the power supply to the torsional driver is switched off. The amplitude decay of free vibrations of a system with viscous damping is described by logarithmic decrement (\( \delta \)), which is defined as the ratio of the natural logarithm of two successive amplitudes of motion. Damping ratio was calculated by using following relationship
The damping ratio was determined at various strain level (Fig 4).

\[ D = \left( \frac{\delta^2}{4\pi^2 + \delta^2} \right)^{0.5} \]  
(3)

The variation of shear modulus with shear strain level (Fig 4).

![Fig. 3 Variation of Shear modulus with shear strain](image)

The variation of Gmax with effective mean stress (\(\sigma_m\)) depends on type of soil, density, degree of saturation etc. G\(_{\max}\) is determined at different confining pressure (1.0 to 4.0 kg/cm\(^2\)) in the Resonant column test. The relation between G\(_{\max}\) and \(\sigma_m\) is given as under:

\[ G_{\max} = 21.7 \times P_a \times K_{2\max} \left( \frac{\sigma_m}{P_a} \right)^{0.5} \]  
(4)

where \(P_a\) = Atmospheric Pressure.

The variation of G\(_{\max}\) with \(\sigma_m\) were determined for soil of earth dam and tailings material under loose as well as compacted condition. (Fig 5). The values of modulus K\(_{2\max}\) for soil of earth dam, tailings material - loose and compacted conditions are found to be 80, 45 and 55 respectively.

![Fig. 5 Variation of Shear modulus with mean stress](image)

**Cyclic Triaxial Tests**

Cyclic strength of the embankment soil, tailings materials—loose as well as compacted were determined from the cyclic triaxial tests. In each test, soil specimen was subjected to confining pressure and axial cyclic loading having uniform amplitude with frequency of 1 cycle per second. The measure of cyclic strength is the cyclic stress ratio (CSR), which is the ratio of amplitude of cyclic axial stress to effective mean confining pressure for given level of strain or pore pressure. CSR for tailing materials under loose condition and compacted condition were found to be 0.325 and 0.46 respectively. (Fig 6)

**STATIC STRESS ANALYSIS**

A computer program FEADAM was used to carry out static stress analysis. The composite section consisting of the earthen dam with tailing deposit and proposed dyke was idealized into 272 finite elements and 290 nodes (Fig 7). Four noded, isoparametric elements were used for the 2D plane strain analysis. Construction sequence of the earthen dam was simulated using the non-linear strength parameters (Table 2). The pre-earthquake normal (\(\sigma_x, \sigma_y\)) and shear stresses \(\tau_{xy}\), existing at
each element was determined. Effective mean stress ($\sigma'_m$) at each element was computed from normal stresses which was used to evaluate maximum dynamic shear modulus ($G_{\text{max}}$) of each element (eqn. 4). This was used as input in the subsequent dynamic response analysis.

DYNAMIC RESPONSE ANALYSIS.

The analysis was carried out for site specific Design Basis earthquake (DBE) having peak ground acceleration of 0.08g (H) and 0.05 g (V). The time step of the digitized acceleration data was 0.01 sec and total duration being 30 sec. [4] Figure 8 gives site specific horizontal acceleration time history.

Equivalent Number of Uniform Loading Cycles

The cyclic strength curve of tailings were obtained for sinusoidal loading while the output of dynamic response analysis, i.e. shear stress time history are random in nature. In order to make a reasonable comparison between cyclic strength and the induced stresses, the random shear stress time history was converted to Equivalent number of Uniform cycles ($N_{\text{EQ}}$). The average $N_{\text{EQ}}$ for the present study was found out to be 14 cycles. The cyclic strength corresponding to CSR value at 14$^{th}$ cycle of ‘cyclic triaxial tests’ was compared with the ‘maximum shear stresses that are likely to be induced’ obtained from dynamic response analysis.

Assessment of Liquefaction Susceptibility

In cyclic triaxial tests, liquefaction is identified when excess pore pressure generated during the test reaches 100% of confining pressure. However, for tailings material the tests showed that maximum excess pore pressure generated at $N_{\text{EQ}}$ was about 20% of confining pressure. The tests indicated that the loose tailings, compacted tailings and the embankment soil do not show liquefaction susceptibility for $N_{\text{EQ}}$ of 14. Figure 10 gives typical dynamic test result showing axial strain and pore pressure variation with loading cycles.
**ASSESSMENT OF DYNAMIC STABILITY**

The overall dynamic stability of the earthen dam, tailings deposit and dyke was assessed from local Factor of Safety (FoS) against 5% strain level. Local FoS is a ratio of ‘induced shear stress’ to ‘Shear strength’ for each element of the section. The elements which have FoS less than 1.0, would undergo deformation in excess of 5% strain.

Computations showed that most of the elements in the section have strain potential less than 5%, indicating that the dam is safe against excessive deformation. However, few elements on the upstream and downstream slopes of the proposed dyke as well as on tailings deposit have local FoS less than unity. These elements would undergo deformation in excess of 5% strain, due to DBE. This is shown in Figure 11 by shaded elements. This would result in settlement of the dyke.

**CONCLUSIONS**

The dynamic analysis indicated that the earthen dam, tailing deposit, and proposed dyke would not undergo liquefaction due to Design Basis earthquake.

However, the slopes of the proposed dyke and the top layer of tailing deposit would undergo more than 5% strain. This would result in local yielding on the slopes of the dyke and settlement of the dyke into the tailings deposit. In order to prevent yielding and settlement, it is necessary to cover the slopes of the dyke by 2m thick compacted soil and to improve the shear strength of the top layer of tailings deposit such that the minimum SPT penetration resistance value of 15 blows / foot is achieved.

**ACKNOWLEDGEMENT**

The authors are grateful to Shri.S.Govindan, Director for giving permission to publish the paper and Shri. R S Ramteke, Additional Director for his encouragement.

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