Correlation between CBR value and effective strength parameters for engineered fills

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Abstract. It is a tradition in Tanzania to use the California bearing ratio (CBR) value for the design of embankments. To assess the stability of embankments, slope stability calculations are performed, for which the effective strength parameters are needed. CBR values can be determined from the effective strength parameters based on Meyerhof’s general bearing capacity equations. Contrary to that, from a given CBR value, the effective friction angle is not easily calculated directly, as the relationship between the non-dimensional bearing capacity factors and the friction angle is complex. Moreover, only the resulting CBR value is known, not the strength contribution of the effective cohesion. Present study presents results from disturbed samples obtained from test pits and boreholes which were tested in order to determine the particle size distribution curves and Atterberg limits. On representative samples from different soil groups (AASHTO classes), CBR tests were performed to assess the quality of the fill material. Moreover, a set of isotropically consolidated, drained (CID) triaxial tests were carefully planned on the granular materials (AASHTO classes: A-2-4, A-2-6 and A-2-7) in order to investigate the relationship between CBR value and effective strength parameters of the materials when used as fill (normally consolidated conditions) at different stress levels. Based on 18 CID triaxial tests, a correlation was established which can be used directly to calculate effective strength parameters from CBR values.

1. Introduction
Tanzania uses the California bearing ratio (CBR) value in embankment design as opposed to stability calculations, which operate with effective strength parameters.

The purpose of present work was to identify a relationship between CBR values and effective strength parameters of fill materials, based on advanced laboratory tests. A total of 18 isotropically consolidated, drained (CID) triaxial tests were performed to derive the correlations.

The CBR tests and the triaxial tests were carried out using soil material obtained from a project site, and the triaxial tests were planned to apply for site-specific loading conditions. The correlations derived in present note are thus project-specific and applicability to other projects must be considered in each individual case.

2. Strength parameters for granular embankment fills
The planned test focused on embankment fills with CBR = 7 and CBR = 15, representing a range of possible embankment slopes. As the specimens were not prepared at the specified density in the
laboratory, the triaxial tests represent a range of CBR values between 4 and 20, which covers an even wider range than initially planned.

In order to assess the strength parameters from CBR values, strength relations were identified in literature. From the CBR value, the friction angle is not easily calculated directly, as the relationship between the non-dimensional bearing capacity factors in Meyerhof's general bearing capacity equations [1, 2] and the friction angle is complex. Thus, the CBR value was determined based on a range of effective friction angles, based on the Meyerhof equation for bearing capacity for the geometrical constraints in the CBR mould during testing. This resulted in a set of effective friction angles, \( \phi' \) and CBR values proposed by Gregory & Cross [3]. Based on these, the following expression Eq. (1) can be written, which allows for estimation of the effective friction angle from the CBR values:

\[
\phi' = -2.16(\log_{10}(CBR))^2 + 18.4 \cdot \log_{10}(CBR) + 22.0, \quad c' = 0 \text{ kPa}
\]  

(1)

Where \( \phi' (\degree) \) is effective friction angle, CBR (\%) is California bearing ratio and \( c' \) (kPa) is effective cohesion. Based on these, the correlation between the CBR values and strength parameters is illustrated in Figure 1. The strength parameters targeted during the planning stage of the advanced tests are also presented in Figure 1.

![Figure 1. Correlation between CBR and effective friction angle. Application of the relationship to identify strength parameter for CBR = 7 and CBR = 15 is indicated with arrows.](image-url)
3. Field investigations

During field investigations, a number of different tests were conducted on soils to assess their quality as fill materials. First, the disturbed samples obtained from test pits and from the boreholes were tested to determine the particle size distribution and the Atterberg limits. Based on these results, the soils were classified using the AASHTO classification [4]. The AASHTO soil classification scheme is presented in Table 1.

Table 1. AASHTO soil classification system.

| General classification | Granular materials | Silt-clay materials |
|------------------------|--------------------|---------------------|
|                        | A-1               | A-2                | A-3 | A-4 | A-5 | A-6 | A-7 | A-7-5 | A-7-6 |
| Group classification   | A-1a              | A-1b               | A-2-4 | A-2-5 | A-2-6 | A-2-7 | A-2-5 | A-2-6 | A-2-7 |
| Sieve analysis         |                   |                    |       |      |     |      |     |       |       |
| Percent passing:       |                   |                    |       |      |     |      |     |       |       |
| 2 mm                   | <50               | <50                | <51   | <35 | <35 | <35 | <35 | <36   | <36   |
| 420 μm                 | <30               | <30                | <35   | <35 | <35 | <35 | <35 | <36   | <36   |
| 75 μm                  | <15               | <25                | <35   | <35 | <35 | <35 | <35 | <36   | <36   |
| Characteristics of fines smaller than 420 μm |                   |                    |       |      |     |      |     |       |       |
| Liquid limit           |                   |                    |       |      |     |      |     |       |       |
| Plasticity index       | <6                | NP                 | <40   | <41 | <40 | <41 | <41 | <40   | <41   |
| Group index            | 0                 | 0                  | <10   | <10 | <11 | <11 | <11 | <10   | <10   |
| Usual types of significant constituent materials | Sand, gravel and stone fragments | Fine sand | Silty or clayey gravel and sand | Silty soils | Clayey soils |
| General rating as subgrade | Excellent to good | Fair to poor |

The embankments in the project will be constructed of granular materials A-2 and A-1, as this is estimated to be the most likely choice, based on the availability from test pit results and characteristics as fill materials. As A-2 materials (silty or clayey gravel and sand) are the dominating materials, which are suitable for embankment fill, and because they have a lesser subgrade rating than A-1 materials (stone fragments, gravel and sand), focus was on the following materials: A-2-4, A-2-6 and A-2-7.

After the classification, CBR tests were performed on representative samples from the different soil groups, in order to assess the quality of the material.

4. Advanced triaxial tests

In order to validate the relation between the CBR values and strength parameters of the fill materials, defined in Chapter 2, triaxial tests were performed on the selected materials: A-2-4, A-2-6 and A-2-7, prepared at different densities (ranging from loose to dense state). The tests were carried out as consolidated, drained tests (CID) with measurement of volume change and pore pressure. For each material class, specimens were consolidated at different stress levels, to simulate the effect of varying embankment height. This procedure allows for interpolation and extrapolation to cover the expected embankment heights for the project. In total, 18 specified CID tests were performed (three single-stage tests for three materials at two target densities).

As the triaxial tests were used to represent a soil element of the embankment fill under the load of a passing train, the triaxial specimens were prepared to reflect the stress state in these conditions. The stress levels were selected to correspond to different depths, d = 3 m, 6 m and 12 m.
The in situ vertical stress was calculated for the different depths below the railway, based on the unit weight of the embankment material, which was assumed to be 20 kN/m³:

$$\sigma_1' = d \cdot \gamma$$  \hspace{1cm} (2)

Where $\sigma_1'$ (kPa) is in-situ vertical stress, $d$ (m) is depth and $\gamma$ (kN/m³) is the unit weight.

$$\sigma_2' = \sigma_3' = K_0 \sigma_1'$$  \hspace{1cm} (3)

Where $\sigma_2'$, $\sigma_3'$ (kPa) are the horizontal in-situ stresses and $K_0$ (-) is the coefficient of earth pressure at rest. The coefficient of earth pressure at rest can be estimated by the relationship proposed by Jaky [5]:

$$K_0 = 1 - \sin \varphi'$$  \hspace{1cm} (4)

To simplify the procedures in the laboratory when consolidating the triaxial specimens, the in-situ stress conditions were approximated with an isotropic stress field in the triaxial cell. The isotropic stress conditions were calculated from the in situ (anisotropic stress state) effective stresses:

$$\sigma_v' = \sigma_h' = \frac{\sigma_1' + 2\sigma_3'}{3}$$  \hspace{1cm} (5)

Where $\sigma_v'$, $\sigma_h'$ (kPa) are the vertical and horizontal components of the isotropic stress field. Following the initial preparation, the specimens were saturated and consolidated to reach the isotropic stress conditions. After full consolidation under the isotropic stress, the specimens were sheared to failure.

**4.1 Selection and preparation of tested samples**

A general review of the CBR tests for each of the three material tests in the triaxial testing campaign revealed that the CBR value is strongly correlated to the density of the tested specimen. In order to define the target densities for the triaxial test specimens (i.e. the density for CBR = 7 and CBR = 15 as planned), a linear regression model was used, where soaked CBR values are plotted against the dry densities, calculated after immersing the CBR specimens in water. Target densities were found for CBR = 7 and CBR = 15 for each material class.

In Figure 2, all data points for materials A-2 from the CBR tests are plotted together with the linear regression from the initial data for A-2-4, A-2-6 and A-2-7 materials and for all A-2 materials. Each point in Figure 2 signifies a single CBR test. It can be seen that the A-2 regression line lies in-between A-2-4 and A-2-7 materials, which is a good estimate as this represents a material mixed of A-2-4, A-2-6 and A-2-7 materials. Thus, it was estimated that the correlations were applicable for assessing CBR value from dry density for the test materials.
Figure 2. All data points for A-2 materials. Linear regressions from initial data plotted for A-2-4, A-2-6, A-2-7 and A-2 materials (all points).

The specified densities for the triaxial specimens were not reached in the laboratory due to human errors. Thus, the relationship between density and CBR value for each material class, cf. Figure 2, was applied to compute the CBR value for each test, as presented in Table 2. Consequently, the 18 triaxial tests reflect 18 different CBR values, which allows for a broader evaluation of the correlation between CBR value and effective strength parameters.

Table 2. Overview over tested specimens.

| AASHTO class | Specimen number | Dry density [kg/m³] | CBR [%] | Bulk density [kg/m³] | Water content [%] | Dry density [kg/m³] | CBR [%] |
|--------------|-----------------|---------------------|---------|----------------------|------------------|---------------------|---------|
| A-2-4        | 1-A             | 1815                | 7       | 2240                 | 13.5             | 1974                | 20.5    |
| A-2-4        | 1-B             | 1815                | 7       | 2220                 | 14.4             | 1941                | 17.7    |
| A-2-4        | 1-C             | 1815                | 7       | 2200                 | 14.1             | 1928                | 16.6    |
| A-2-4        | 2-A             | 1910                | 15      | 2210                 | 15.3             | 1917                | 15.7    |
| A-2-4        | 2-B             | 1910                | 15      | 2170                 | 15.7             | 1876                | 12.2    |
| A-2-4        | 2-C             | 1910                | 15      | 2200                 | 15.8             | 1900                | 14.3    |
| A-2-6        | 1-A             | 1815                | 7       | 2180                 | 10.6             | 1971                | 17.1    |
| A-2-6        | 1-B             | 1815                | 7       | 2180                 | 13.5             | 1921                | 13.8    |
| A-2-6        | 1-C             | 1815                | 7       | 2080                 | 10.2             | 1887                | 11.6    |
| A-2-6        | 2-A             | 1940                | 15      | 2090                 | 11.1             | 1881                | 11.2    |
| A-2-6        | 2-B             | 1940                | 15      | 2200                 | 11.1             | 1980                | 17.7    |
| A-2-6        | 2-C             | 1940                | 15      | 2180                 | 11.3             | 1959                | 16.3    |
| A-2-7        | 1-A             | 1850                | 7       | 2130                 | 11.7             | 1907                | 10.8    |
| A-2-7        | 1-B             | 1850                | 7       | 2080                 | 15.9             | 1795                | 4.1     |
| A-2-7        | 1-C             | 1850                | 7       | 2080                 | 13.3             | 1836                | 6.6     |
| A-2-7        | 2-A             | 1975                | 15      | 2120                 | 13.9             | 1861                | 8.1     |
| A-2-7        | 2-B             | 1975                | 15      | 2150                 | 15.4             | 1863                | 8.2     |
| A-2-7        | 2-C             | 1975                | 15      | 2150                 | 16.3             | 1849                | 7.3     |
4.2 Triaxial test type and post-processing of the data
To minimise the complexity of the advanced testing, the CID test with measurement of excess pore pressure was chosen. During this type of testing, the shear rate is selected to ensure a drained response, which is validated by the excess pore pressure measurements. Hence, the effective stress path for the specimens is known throughout the test. For the specific tests, the shear rate varied between 0.2 and 0.45 mm/min.

To enable identification of the effective stress path during the tests, the shear phase was evaluated in the \( p' - q' \) diagram, which illustrates the actual path followed during testing, and not only the failure state, as illustrated in the classic \( \tau - \sigma' \) diagram with Mohr's circles. The procedure adopted in the present tests ensures that the failure state is reached in the tests. Moreover, the deviator stress was plotted against the axial strain to enable identification of failure for each test. In the present paper, only the failure state is presented in the presented \( p' - q' \) diagram.

5. Results of triaxial tests

5.1 Post-processing of lab results
After completion of the triaxial tests, the raw data files (one for each test) were received, containing measurements of the following variables for the shear phase:

- Time
- Cell pressure
- Back pressure
- Pore pressure
- Applied force
- Displacement
- Volume flow.

As the specified densities were not reached during testing, it was not possible to group three identical specimens for evaluation of stress-dependent strength parameters. Thus, from each triaxial test, a secant friction angle was identified. The triaxial tests were analysed using the \( p' - q' \) diagram:

\[
p' = \frac{\sigma'_v + \sigma'_h}{2} \tag{6}
\]
\[
q' = \frac{\sigma'_v - \sigma'_h}{2} \tag{7}
\]

The vertical and horizontal stresses were computed as follows:

\[
\sigma'_h = u_{\text{cell}} - u_{\text{sample}} \tag{8}
\]
\[
\sigma'_v = \sigma'_h + \frac{F_{\text{piston}}}{A_{\text{specimen}}} \tag{9}
\]

Where \( u_{\text{cell}} \) (kPa) and \( u_{\text{sample}} \) (kPa) are the pressure readings from inside the cell and inside the sample, respectively, and \( F_{\text{piston}} \) (kN) is the force reading during the shear phase. \( A_{\text{specimen}} \) (m²) denotes the area of the specimen. The effect on the axial strain and the change in volume during shear on the area of the specimens were accounted for during interpretation of the results. The deviator
stress \(2q'\) was plotted against the axial strain for each of the specimens. These plots were corrected for improper fitting of the piston in the upper pressure head, which is why the plots are labelled "corrected deviator stress".

The plots were used to evaluate the onset of failure during tests. Generally, the triaxial tests fell in two groups regarding shear response: One group showed distinct peak behaviour, and the other group showed continued increase of the deviator stress until end of test. Thus, the failure criterion was defined as the peak value of the deviator stress or the deviator stress at \(\varepsilon_A = 10\%\). In some cases, slightly higher deviator stress was observed for larger strains, but to ensure strain compatibility between the tests, the presented failure criterion was applied. The identified failures were verified in the \(p' - q'\) diagrams to verify that the stress path reached a state of failure.

The \(p' - q'\) diagram was plotted for each test specimen. Based on the failure envelope, the effective strength parameters associated with the Mohr-Coulomb failure criterion can be calculated, applying the condition of the effective cohesion being equal to zero. The slope of the failure envelope in the \(p' - q'\) diagram, \(\theta\), is related to the effective friction angle as follows:

\[
\sin(\phi') = \tan(\theta)
\]

\[
c' = \frac{a}{\cos(\phi')}
\]

Where \(c'\) (kPa) is the effective cohesion, and \(a\) (kPa) is the intercept between the failure envelope and the \(q'\)-axis in the \(p' - q'\) diagram.

The same procedure was followed for all the 18 tests, thus 18 effective friction angle values were determined. As the dry densities in the tests did not match the specified ones, the CBR value for each test was calculated with the relations between CBR value and dry density of each material type, as described in Chapter 4.1, cf. Table 2. Based on these, the CBR values were plotted against the effective friction angles in Figure 3. Here, the correlation described in Chapter 2.1 is also plotted.

It can be seen that the results of the triaxial tests are close to the correlation found in the literature. Most of the data points are slightly above this correlation. Accounting for the scatter observed in the density vs. CBR value plots, the effective friction angles calculated from Eq. (1) may be considered as a characteristic value. Thus, for purely frictional response (without \(c'\)), the relationship presented in Eq. (1) is verified, based on the performed tests.
5.2 Strength model with effective cohesion

As all three materials contain a small proportion of clay-sized material, they may be viewed as materials with a (small) effective cohesion. As presented in Chapter 2, the range of CBR values analysed in the preliminary design is $CBR = 7 - 15$. Selecting the tests performed within this CBR interval and plotting the results together enable derivation of a joint set of strength parameters, $\phi'$ and $c'$. The joint failure envelope for triaxial tests, where the density corresponds to $CBR = 7 - 15$, is illustrated in Figure 4.

It should be noted that the joint failure envelope illustrated in Figure 4 is based on tests of specimens prepared with different densities. However, the failure envelope represents an estimate of the average parameters for the fill materials. The failure envelope interception with the y-axis corresponds to $c' = 5$ kPa. Assuming that $c' = 5$ kPa is applied generally for the tested materials, the secant friction angle, reflecting the identified failures, and $c' = 5$ kPa may be derived. These values are presented in Figure 5.

The correlation for this case was derived, and is presented in Eq. (12).

$$
\phi' = -2.16(\log_{10}(CBR))^2 + 18.4 \cdot \log_{10}(CBR) + 19.9, \quad c' = 5 \text{ kPa}
$$

Figure 5. Correlation between $CBR$ and effective friction angle from triaxial tests. Assumed effective cohesion $c' = 5$ kPa.

6. Conclusion

Based on a series of advanced, isotropically, consolidated drained triaxial tests, on three different material classes of likely embankment fill, a link between the $CBR$ value and the strength parameters was derived and presented. Based on the available results, one may choose to express the correlation with or without effective cohesion, based on two equations presented in the current paper (Eq. (1) and (12)). The results presented are valid for granular materials of AASHTO classes A-2-4, A-2-6 and A-2-7. In case other materials are to be used as embankment fill materials, further testing is recommended.
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