CHARACTERISING RAILWAY SUBSTRUCTURE LAYERS FOR REHABILITATION DESIGN

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ABSTRACT

Current railway substructure design methods rely heavily on an accurate assessment of the in-situ material properties, particularly the modulus of the subgrade and substructure layers. This information is used in foundation design models to determine the required cover to prevent deformation and failure of support. This paper presents typical data obtained during a rehabilitation design investigation to accurately evaluate the modulus of the in situ subgrade and substructure layers using Pencel pressuremeter tests, dynamic cone penetrometer tests, deflection measurements through remote video monitoring and lightweight drop-weight tests. Standard soil parameters related to the grading, plasticity and CBR of the investigated materials do not have any direct relationship with the modulus values that were obtained. This is specifically true for sand materials where good or poor CBR and plasticity values can give a misleading indication of the formation modulus.

1 INTRODUCTION

The railway substructure designer is confronted with a number of evaluation techniques when considering the rehabilitation of an existing railway line. The SAICE (2010) Code of Practice for site investigations states that the following methods can be included in the geotechnical investigation depending on the engineering structure and the complexity and variability of the geotechnical conditions:

- Geophysics/remote sensing
- Reflection and refraction seismic surveys
- Magnetic surveys
- Gravity surveys
- Resistivity surveys
- Continuous Surface Wave tests
- Electromagnetic surveys
- Ground penetrating radar surveys
- Infrared, radiometric and light detection and ranging (LIDAR) surveys.
- Penetrometers (including DCP/DPSH/SPT/CPT & CPTU)
- Test holes/auger holes/geotechnical drilling/percussion drilling

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- Laboratory testing including grading analysis, linear shrinkage, liquid limit, plastic limit, determination of the maximum dry density and optimum moisture content, California Bearing Ratio

For linear structures, like railway lines, a data frequency of five test points per kilometer is proposed for detail design. The last two methods (test pitting and laboratory testing) would generally apply as a minimum for uncomplicated rehabilitation works.

For the rehabilitation design of other linear structures like roads, a number of rehabilitation design procedures have been developed of which TRH 12 (1997) would form the baseline in a South African context. International methods include those developed by AASHTO (1993) and the TRL (1999). These methods rely heavily on deflection data, but riding quality, rutting (wheel path deformation), laboratory testing, etc. are also considered.

Most of the internationally recognized railway substructure design techniques are empiric and include those developed by UIC (2008), AREMA (2008), S410 (2006), Shahu et al. (2000) and Li and Selig (1998). Input values for in situ material properties rely to a large extent on CBR and stiffness values. Currently the tendency is to use a more mechanistic approach where accurate layer stiffnesses are essential. Accordingly, recent rehabilitation investigations on heavy haul lines included point load measurements (Fortunato et al., 2010) and Benkelman beam deflections (Muniz et al., 2005) to obtain stiffness parameters.

This paper provides some insights into the value of different properties measured during a typical rehabilitation design. Data gathered on typical Southern African heavy haul lines were statistically analyzed and compared and provide the designer with information that would assist in the selection of the most appropriate methods to use during a geotechnical investigation of an existing railway line. Data was gathered during the dry season (September and October). A summary of the basic field conditions related to the data analyzed, is provided in Table 1.

Table 1: Summary of basic field conditions for study area

Country	**Climate**			**Topography**	**Typical range of substructure material properties**		
	Description	**Rainfall (mm/year)**	**Temperature (◦C)**		**GM**	**PI**	**CBR @ 95% Mod. AASTHO**
Malawi	Semi-arid	800 - 1000	18 - 28	Flat with some hills	1.3 - 1.8	0 - 12	6 - 14
Mozambique	Sub-tropical to semi-arid	800 - 1200	18 - 32	Flat with some outcrops	1.1 - 1.5	5 - 12	8 - 26

2 INVESTIGATION METHODOLOGY

During the current investigation, the following methods, equipment and soil tests were evaluated and used:

A. Standard tests on 385 soil samples at 351 testing locations:

- Standard laboratory testing including the determination of Atterberg limits, grading analysis, maximum dry density and optimum moisture content, California bearing ratio (CBR) at 90%, 93%, 95%, 98% and 100% Mod. AASHTO density and CBR swell at 100% Mod. AASHTO density.

B. Specialist tests on 31 soil samples at 18 testing locations:

- Pencel pressuremeter tests.
- Dynamic Cone Penetrometer (DCP) tests.
- Light Weight Deflectometer (LWD) measurements.
- Deflection measurement through Remote Video Monitoring (RVM).
- Standard laboratory testing as for A above.

In this section the different methods are briefly described and their advantages and disadvantages highlighted.

2.1 Pencel Testing

The Pencel pressuremeter is a single cell pressuremeter system and is a derivation of the Menard pressuremeter. The Pencel pressuremeter test consists of placing an inflatable cylindrical probe into a predrilled hole and expanding the probe with water while measuring the change in volume and pressure in the probe. Figure 1 shows the apparatus and a typical installation arrangement. The purpose of pressuremeter tests is to characterize the stress-strain relationship (modulus) of the in situ formation layers for existing track formation layers and to determine the formation condition of a section (Shaw, 2005).

Figure 1: The Pencel pressuremeter with water reservoir, pressure chamber and probe (left) and a photo of a typical test pit where the whole for insertion of the probe is being drilled (right)

The Pencel probe comprises a cylindrical body, fitted with an inflatable membrane, fluid inlet and saturation ports. The probe is connected to the control and measuring unit with a hydraulic pipe. This unit contains a cylindrical reservoir with a piston, control valves, pressure and volume gauges (Gräbe, 1997). The test method and calibration of the Pencel is described in the ASTM standard (ASTM D4719-87, 1987).

A first set of instrument compliance readings are taken with the probe at the height of the pressure gauge. These 'pressure to volume' readings will be subtracted from the actual pressuremeter test readings to obtain the resultant pressure that is exerted on the material outside the probe. The probe is then inserted horizontally in the testing position. A new set of readings of pressure and volume is taken at the same intervals as the compliance readings. As before, the probe is inflated at equal increments of volume. An unload-reload cycle is usually performed at the end of the linear portion of the pressuremeter curve. It is this gradient of the reloading cycles that is used to determine the in situ material properties (Gräbe, 1997).

Generally, the Pencel testing systems currently available are not automated and the fact that test pitting is required for the insertion of the probe, makes the test extremely time consuming (average of one test location per day for this project). The Pencel test has been used extensively in South Africa, particularly on the coal line and considerable confidence has been gained with the modulus readings that it provides. The numerical analysis and substructure design based on the standard S410 (2006) specification, emanated from this work.

2.2 Remote Video Monitoring

Remote Video Monitoring (RVM) is a special application of Particle Image Velocimetry (PIV). PIV is a measuring technique that originated in the field of experimental fluid mechanics (Adrian, 1991). In recent developments it has been used to measure soil deformation in soil laboratory testing (White et al., 2003 and White & Bolton, 2004) as well as for measuring landfill settlement (White et al., 2003). The RVM used in this study is based on work by Bowness et al. (2006).

The RVM system comprises a video camera which captures video images of a target attached to the track structure at a rate of approximately 25 images per second as typically shown in Figure 2. The images are analysed by using image analysis software which calculates the horizontal and vertical displacement of the target. The target can be attached to any part of the track structure, e.g. the rail, sleeper or formation. The video camera is positioned at some distance from the track to be independent of the normal track deflection as well as terrain vibrations.

The advantages of this technique include the separation of deflections originating from formation layers and the possibility to measure a complete deflection curve. However, the need for a locomotive with known axle loads as well as difficulties with fixing of the targets and natural lighting on site, complicate the measurements.

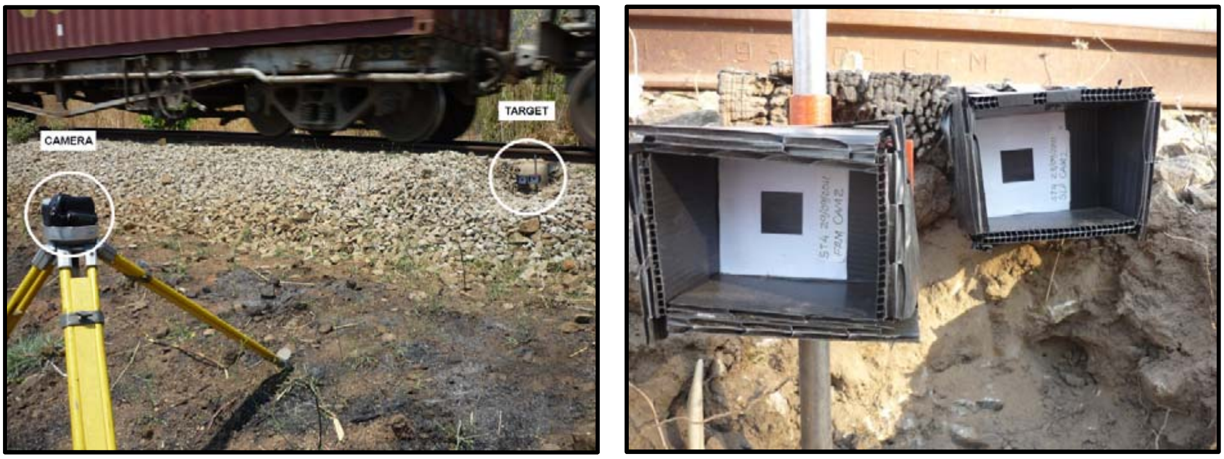

Figure 2: The RVM system comprising video camera and targets on the track structure (left) and a close up of the targets fixed to a formation reference rod and a wooden sleeper (right).

2.3 The Dynamic Cone Penetrometer

The Dynamic Cone Penetrometer (DCP) has been used for a number of years by engineers in South Africa as a non-destructive testing (NDT) device to measure the in situ bearing capacity of pavements. The DCP consists of an upper fixed travel rod with an 8 kg falling weight, a lower rod containing an anvil and a replaceable cone. The test is conducted by dropping the weight from the fixed height and recording the number of blows versus depth.

The DCP instrument measures the penetration per blow into a pavement through each of the different pavement layers. This penetration is a function of the in situ shear strength of the material. The profile in depth of the pavement gives an indication of the in situ properties of the materials in the pavement and insitu layers (TRH 12, 1997). The DCP allows for detailed evaluation and analysis of pavement structures and their different layers (Jordaan, 1994) and has the ability to verify both the level and the uniformity of compaction. The disadvantages of the method include the need to consider field moisture levels and erroneous readings obtained when testing material with large aggregates (Van Wijk et al, 2007).

2.4 Light Weight Deflectometer Testing

The Light weight falling weight Deflectometer (LWD) is a relatively new NDT device used to measure the in situ stiffness of pavements. It is a scaled down version of the conventional Falling Weight Deflectometer (FWD).

The LWD weighs approximately 26 kg and includes a 10 kg falling mass that impacts on the bearing plate via four rubber buffers to produce a load pulse of 15 to 20 milliseconds and a load range of 1 to 15 kN. It has an adjustable falling height, adjustable falling mass and additional loading plates. Therefore different contact pressures can be produced, accommodating different soil types (Horak & Khumalo, 2006; Nazzal, 2003 and Hoffmann et al., 2004). For this study a 10 kg weight was dropped from a height of 850 mm onto a 300 mm load plate.

The LWD uses two types of sensors: a load cell for measuring the impact force from the falling weight, and a geophone that measures the velocity of the surface from which deflection is determined by integration.

With this model, the reaction of the soil to the shock-waves can be measured by up to three geophones that extend radially outward from the unit. The output includes respective time histories and peak values of the applied load and ensuing deflection, as well as an estimated value of the soil elastic modulus (Hoffmann et al., 2004). A complete analysis of the LWD field data can provide an estimate of the linear elastic response of the individual layer materials making up the pavement structure.

The disadvantages of using this device include the timeous removal of the ballast for testing and the fact that it has not yet been proven in industry.

2.5 Laboratory testing

Of all the methods discussed, laboratory testing can be the most costly and time consuming as it required a test pitting exercise to extract the material. It however provides other essential information such as the visual condition of the material, moisture condition and deterioration or carbonation of stabilized layers. Typically during a rehabilitation design investigation, the following material properties will be assessed:

- Grading (TMH1 method A1).
- Atterberg limits (TMH1 method A3 and A5).
- California bearing ratio (TMH1 method A7 and A8).

Generally, the use of more sophisticated test methods to determine stiffness and deformation properties such as the triaxial or K-mould tests have been limited (Van Wijk et al., 2007) and were not considered during the current investigation.

3 ANALYSIS

The data obtained during the field investigations were analyzed using multivariate theory to determine the correlation between the different measurements. At first the data set as a whole was considered and then the data was divided into two subsets, based on the in situ soil properties, in an effort to better understand the interrelationships between the different methods.

3.1 Multivariate Analysis theory

The correlation coefficient $\rho_{x,y}$ forms the basis of multivariate analysis (Bowker and Lieberman, 1959). It is used to determine whether two ranges of data move together, that is, whether large values of one set are associated with large values of the other (positive correlation), whether small values of one set are associated with large values of the other (negative correlation), or whether values in both sets are unrelated (correlation near zero).

The equation for the correlation coefficient is:

$$\rho_{x,y} = \frac{Cov(X,Y)}{\sigma_x \cdot \sigma_y} \qquad \text{(Eq. 1)}$$

where

$$-1 \le \rho_{x,y} \le 1$$

$$Cov(X,Y) = \frac{1}{n}\sum_{i=1}^{n}(X_i - \mu_x)(X_i - \mu_y)$$

3.2 Correlation results

Figure 3 shows a schematic representation of the correlations between different soil parameters of the entire specialist testing data set, the larger the circle, the better the correlation between the two parameters. In this graph the sign of the correlation coefficient was not taken into account.

The modulus parameters (i.e. Young's or E-modulus calculated from the Pencel pressuremeter, LWD, DCP and CBR tests) and RVM data do not show significant correlations with any of the other parameters when all data is used. A reasonable correlation is observed between the Pencel and the LWD modulus values. The only parameters showing significant correlations are the parameters related to grading (i.e. % Gravel, % Sand, % Silt and Clay and Grading Modulus) and plasticity (i.e. Plasticity Index, Liquid Limit and Linear Shrinkage).

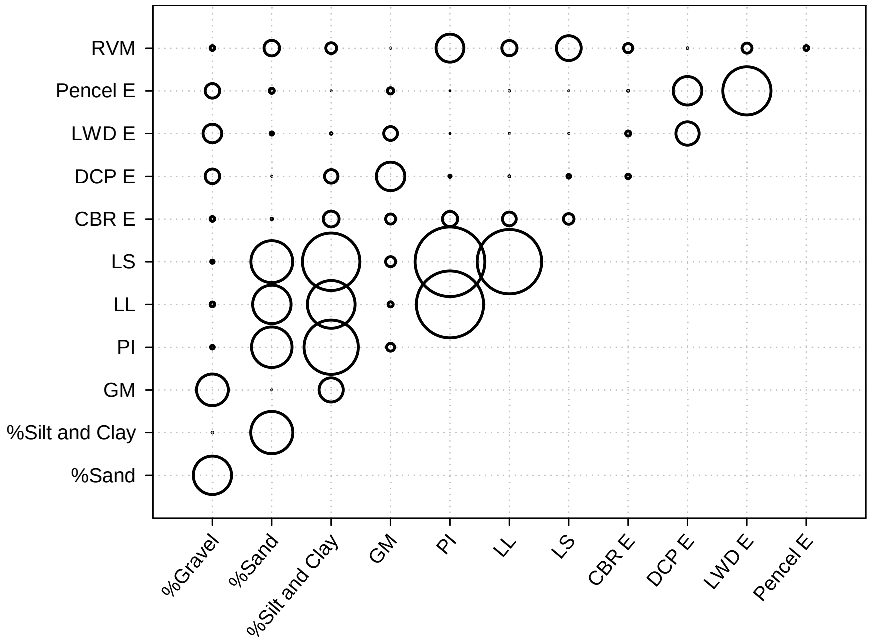

Figure 3: Correlations between soil parameters: All data (specialist tests)

The strongest correlation, despite the fact that the entire data set was analyzed, is found between the Plasticity Index (PI), Liquid Limit (LL) and Linear Shrinkage (LS) parameters.
As a result of the weak correlation coefficient results, the data was sorted into two groups (clays and sands apart). The clay and silt content was used to distinguish between clays (>15%) and sands (<15%). In addition, the plasticity index was used to decide on the classification of materials with high clay and silt content but low plasticity. The results of the multivariate analysis on the two separate groups of data changed dramatically and now many more correlations are visible, especially between the E-modulus values, RVM data and the other parameters. Figure 4 and Figure 5 shows the correlation results of the clay and sand materials respectively.

Figure 4 shows significant correlation between the measured track deflection (RVM data), the type of material, and the plasticity parameters. The modulus parameters, especially those calculated from the Pencel pressuremeter, the LWD and the DCP show significant correlation. In terms of all the parameters, the Pencel E-value and LDW E-value show the least correlation with other parameters.

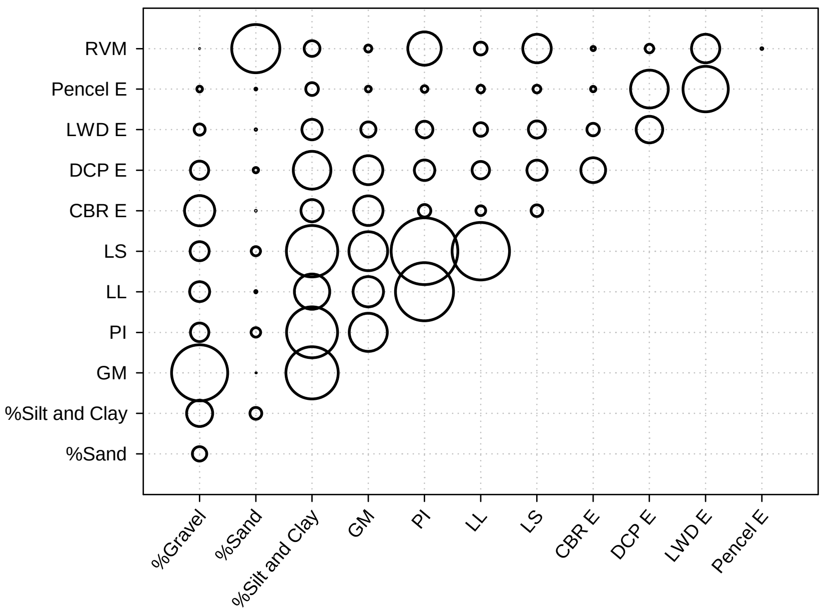

Figure 4: Correlations between soil parameters: Clay materials (specialist tests)

Compared to the clay materials, the sand materials show very little correlation between the Pencel E-values and the LWD E-values and any of the other parameters as shown in Figure 5. The implication of this finding is that sandy materials with low DCP and CBR values might erroneously be viewed as low quality or low stiffness materials in the absence of any specialist in-situ tests that measure the stress-strain response of the specific layer under consideration.

To conclude the analysis of the data, multivariate analyses were carried out on the standard testing soil parameter results for a comparison with the same parameters obtained from the specialist testing samples. Figure 6 demonstrates that the two sand material data sets have different soil parameter correlations while the two clay material data sets have similar soil parameter correlations. This observation is in line with the observations discussed in the previous paragraphs.

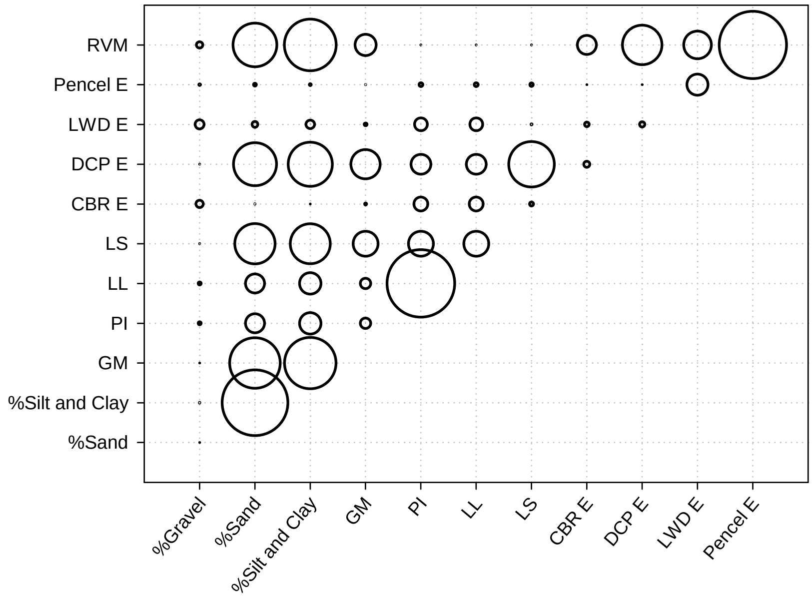

Figure 5: Correlations between soil parameters: Sand materials (specialist tests)

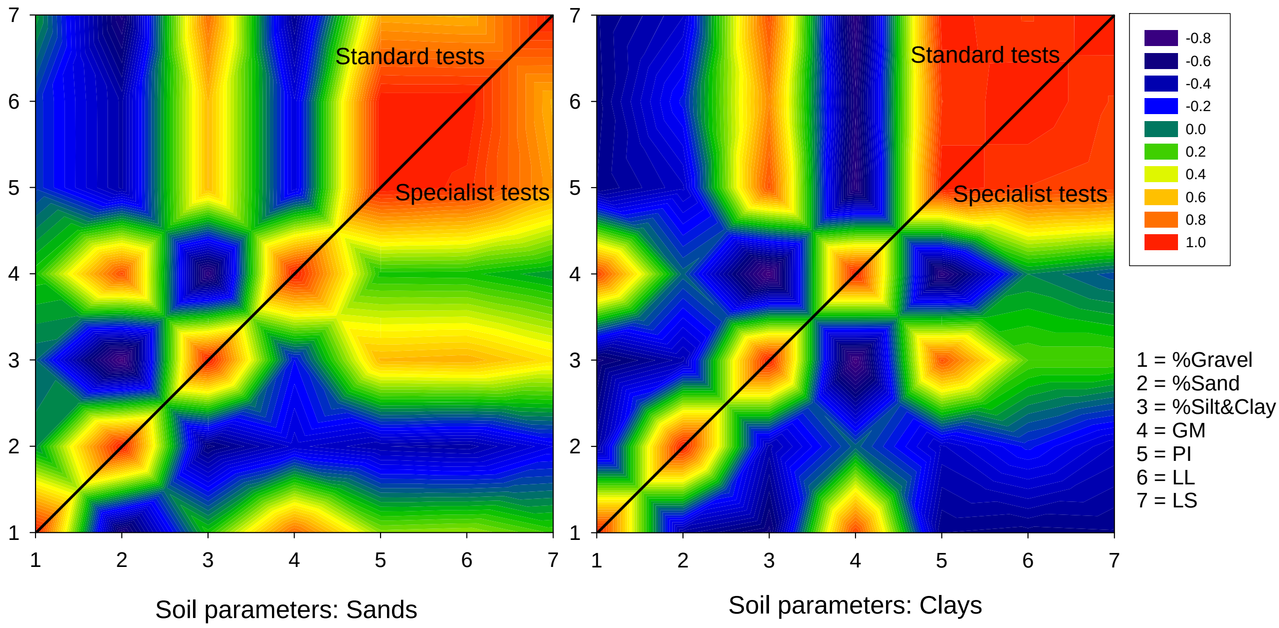

Figure 6: Correlations between soil parameters: All data sets

4 CONCLUSION AND RECOMMENDATION

The multivariate analysis results on the clay and sand materials individually indicate that the standard soil parameters related to the grading, plasticity and CBR of the investigated materials, do not have any direct relationship with the modulus values that were obtained by carrying out specialist testing. This is specifically true for sand materials where good or poor CBR and plasticity values can give a misleading indication of the formation modulus. For these in situ conditions specialist testing (Pencel pressuremeter or Remote Video Monitoring) will be required.

In areas with clayey soil conditions, the use of the LWD and DCP can be considered to obtain good estimates of in situ stiffness values. Both these devices are relatively easy to operate and a high test frequency can be used. In situ moisture content should however be monitored.

Substructure rehabilitation design and the determination of material properties are complex issues and a holistic approach whereby all available methods are considered and the appropriate ones used, should be applied. A greater quantity of comparative specialist testing in a greater spectrum of areas is suggested for further study and research.

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