Use of the Light Weight Deflectometer (LWD) at Highland Valley Copper Mine

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ABSTRACT
The Light Weight Deflectometer (LWD) is a hand portable version of the falling weight deflectometer typically used for paved road evaluations. It is currently underutilized in North America, although it is gaining acceptance by several American state Departments of Transportation for compaction Quality Assurance. The LWD provides a measurement of the dynamic modulus of elasticity of the soil that is comparable with the static modulus of elasticity determined with the Static Plate Bearing Test.

Since early 2008, this equipment has been used at the Highland Valley Copper mine site (HVC) for compaction quality control/assurance of coarse grained aggregate foundations, road bases and earth dam fill materials. In some cases, the LWD was used in conjunction with Nuclear Densometer testing to assess the relationship between in situ dry density and the dynamic modulus of elasticity. This paper includes a discussion on this potential relationship.

This paper describes the use of the LWD at the L-L Tailings Dam, the ore stockpile cover foundations, fuel tank station, and at the multiplate overpass foundations and backfill. A comparison of the LWD capabilities with alternative field testing measures is presented along with an evaluation of its effectiveness at HVC.

RÉSUMÉ
Le déflectomètre à faible masse (LWD), version portative du déflectomètre à masse tombante (FWD) est utilisé typiquement pour l'évaluation de chaussées flexibles. Présentement, le LWD, qui procure une bonne évaluation de la compaction faite sur le terrain, est surtout utilisé en Amérique du Nord, mais devient de plus en plus une référence pour le Département des Transports des États-Unis. Plus précisément, le LWD permet de mesurer le module d'élasticité dynamique d'un sol.

Depuis 2008, le déflectomètre à faible masse est largement utilisé sur le site minier de la Highland Valley Copper (HVC). Entre autres, le LWD sert de guide pour le contrôle de la compacité des fondations d'aggrégats de grains grossiers, les semelles de routes et les matériaux de remplissage des digues en terre. Cet article discute de l'approche de la relation entre la masse volumique sèche et le module d'élasticité dynamique.

Cet article décrit l'utilisation du LWD sur des digues de rejets miniers, des fondations des réserves de minerai, des stations de réservoir à carburant et aux fondations des infrastructures. Tout au long de l'article, les résultats provenant de HVC menés par l'appareil sont comparés avec d'autres instruments de mesure afin d'en démontrer son efficacité.

1 OVERVIEW OF THE LWD

1.1 General Description

The Light Weight Deflectometer (LWD) was developed in Europe to measure the in situ dynamic modulus of soils. The LWD is similar to the falling weight deflectometer (FWD) used for roadways, but is portable with a weight of approximately 15 kg to 25 kg, can be operated by 1 person and the test can be done in 1 to 2 minutes.

Figure 1 shows the typical components of a LWD tester, which comprise a loading device consisting of a 10 kg drop weight mounted on a rod with a spring (damping device) at the bottom and a latch at the top to hold the weight and achieve a uniform drop of 700 mm. The loading device is placed on a 20 mm thick and 300 mm diameter steel plate instrumented with an accelerometer hooked up to a portable electronic data acquisition system. The equipment is calibrated to deliver a maximum impact load of 7.07 kN and impact duration of 18 ms. The device is configured assuming that the plate is sufficiently rigid to move with the soil and the impact load is constant. Soil deformations are calculated by integration of the accelerometer readings. During operation, the plate is first placed directly over level ground and 3 initial blows of the drop weight are given to ensure a close contact. A subsequent 3 drops of the weight are performed and the data acquisition system calculates the deformation (deflection) for each blow and the soil's dynamic modulus E_{vd}. A printout or downloadable trace of the accelerometer readings can then be generated (Figure 2).

The dynamic soil modulus (E_{vd}) is calculated by Equation 1, where r is the radius of the load plate, σ is the stress below the plate and s is the measured deflection or settlement.

$$E_{vd} = 1.5\, r\, \sigma / s \qquad [1]$$

The LWD is gaining acceptance in North America, particularly by several US State Departments of Transportation (Mn/DOT 2010) for compaction control of the pavement structure, measuring modulus instead of soil density. The LWD has only recently been introduced into Canada. The LWD provides different information than traditional in situ soil density measurements, which may be advantageous to construction control and design. For example, measurements of dynamic modulus (E_{vd}) can range nearly an order of magnitude instead of a few percentages, the tests are not destructive as the soil is not penetrated, the tests can be performed in relatively narrow trenches and in close proximity to metal elements, and the equipment is robust and has no source of radiation. The real value of the LWD is in use on gravelly or cobbly soils where other methods, such as the nuclear densometer, are not suitable and in the detection of less dense layers at depths greater than 300 mm (maximum testing depth of the nuclear densometer).

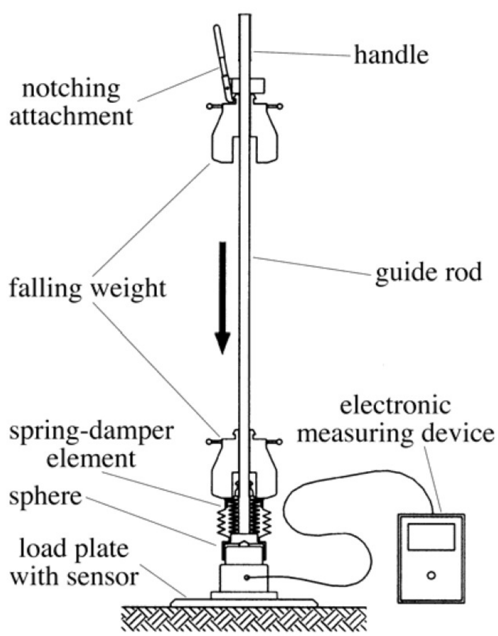

Figure 1. Schematic of the LWD (from Adam and Adam 2003)

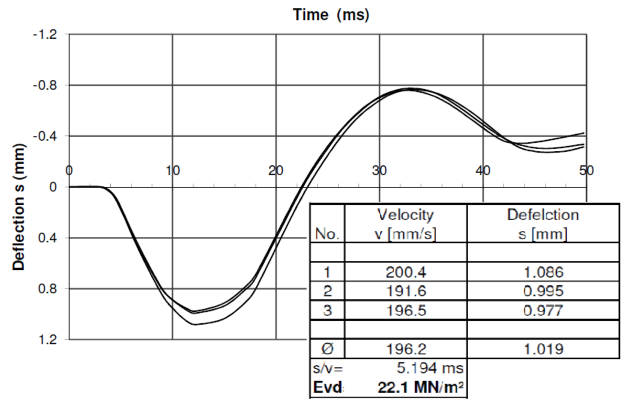

Figure 2. Output from the LWD (from Zorn 2005)

The correlation between E_{vd} and degree of compaction varies with soil type and moisture content as well as with compactive effort. Table 1 illustrates the measured relationship between E_{vd} and degree of compaction, as compiled by the German Road and Transport Research Association (FGVS 1997), for a broad range of soil types.

Table 1. Correlation of Degree of Compaction and E_{vd} (from FGVS 1997).

Soil Group	Degree of Compaction D_{Pr}	Modulus of Resilience E_{vd}
DIN 18 196	%	MN/m^2
GW, GI, GU_1, GT_1 as per ZTVT	≥ 103	≥ 60
GW, GI, GU, GT as per ZTVE	≥ 100	≥ 50
	≥ 98	≥ 40
	≥ 97	≥ 35
GE, SE, SW, SI	≥ 100	≥ 40
	≥ 98	≥ 35
	≥ 97	≥ 32
Mixed-grain soils: GU_2, GT_2, SU, ST e.g. stony soil	≥ 100	≥ 35
	≥ 97	≥ 25
Fine grained soils: U, T	≥ 97	≥ 25
Mixed grain soils GU, GT, SU, ST	≥ 95	≥ 20

1.2 Comparison with Other Techniques

Engineered fill or prepared subgrade compaction control has traditionally been carried out by density measurement using sand cones or nuclear densometers which relate soil properties to the measured or inferred soil density. Alternatively, the soil properties can be measured or calculated by direct measurement of the response of the soil to applied loads or correlated to penetration resistance of various probes. The response of the soil can be measured using the static plate test, LWD, Clegg Hammer, GeoGauge, time domain reflectometry and other means. Penetration resistance can be conducted with portable penetrometers by measuring the number of blows for a given penetration or the penetration per blow.

Nuclear densometers, commonly used as standard density testing equipment, operate by inserting a probe into the ground to a depth of up to 300 mm and measuring the photon radiation transmitted through the soil with a detector located at the base of the equipment. The soil density is inversely proportional to the number of photons transmitted through the material. Density measurements are subject to errors created by the presence of large aggregate particles in the material that need to be considered when comparing to the density of the soil as determined in the laboratory or that cause voids in the vicinity of the gamma radiation source as the probe is inserted in the ground. The moisture is determined using a neutron source and a helium 3 detector located inside the gauge just above the surface of the test material. The detector measures the neutrons that are slowed after interacting with the hydrogen in the soil, which relates directly to the amount of moisture in the sample. Moisture measurements are subject to errors due to hydrogen sources in the soil other than that in the water. The density of the soil is compared to the maximum density of the soil as determined by standard Proctor density laboratory tests. The nuclear gauge is considered to be hazardous equipment and is subject to stringent government licensing for use and transportation of hazardous materials. The nuclear gauge is a very useful tool in uniform soils, but has limitations. Other direct measures of density are available, such as sand cone and volumeter but most are time-consuming and can be difficult to implement particularly in coarse grained soils.

Mooney et al. (2008) presents a review of the various compaction control methods and their use in Minnesota. The static plate load test is expensive and slow, but produces repeatable results. The LWD is a quick and repeatable test that is not influenced by large aggregate, proximity to metal reinforcement and fill end effects. However, the soil modulus determined by the LWD is moisture sensitive for low permeability soils or for saturated high permeability soils. The Clegg Hammer where a weight impacts the ground directly is a quick, repeatable test. However, the resulting Clegg Impact values calculated from the measurements of the accelerometer mounted at the top of the hammer are moisture sensitive and vary with the weight of the hammer. The GeoGauge produces vibrations at various frequencies and the equipment measures the resulting soil deformations. The calculated soil stiffness by the GeoGauge has been found to be unreliable in tests as the equipment is very sensitive to seating conditions, as determined by various State Departments of Transportation and its use has been discouraged. The Time Domain Reflectometry (TDR) equipment uses electromagnetic wave propagation to estimate moisture content and density. The TDR is typically calibrated with Proctor density tests in the laboratory, but the equipment requires inserting multiple probes into the ground and is very sensitive to the presence of coarse aggregate. The portable Standard Dynamic Cone Penetrometer (DCP) comprises a drive rod fitted with a cone at the tip and is operated by dropping an 8 kg mass from a specified height. The DCP produces results that can be correlated well to the California Bearing Ratio (CBR) and other soil parameters and can be used to about 1.2 m depth. The DCP may require 2 people to operate and take readings, may be time consuming in dense soils when testing deeper materials and may produce erroneous test results when large aggregate is encountered.

2 USE OF THE LWD AT HIGHLAND VALLEY COPPER

The LWD has been used at HVC by Klohn Crippen Berger (KCB 2010) for the last two years to monitor foundation and compaction works for the following projects: embankment construction at L-L Dam (summer 2008), ore stockpile cover foundations (early 2008 to 2010), a haul road multiplate overpass (fall 2009); and at a new fuelling station adjacent to the Valley Pit (summer 2008). The LWD has been used for compaction control independently or in conjunction with a nuclear densometer.

2.1 Site Description

The Highland Valley Copper Mine is located about 15 km west of Logan Lake, approximately 75 km southwest of Kamloops, in the interior of British Columbia (Figure 3). The Highland Valley runs northwest from the mine site towards Ashcroft and the Thompson River.

Figure 3. Highland Valley Copper Mine Location

Currently, HVC operates the Lornex Pit, the Valley Pit and the Highland Tailings Storage Facility. The latter is impounded in the Highland Valley and is contained by the L-L Dam and the H-H Dam (Figure 4), with the H-H

Dam at the upstream end within three kilometres of the pit, and the L-L Dam located at the downstream end, 10 km to the northwest (Figure 5). The mill site and main mine access are located between the Valley and Lornex pits.

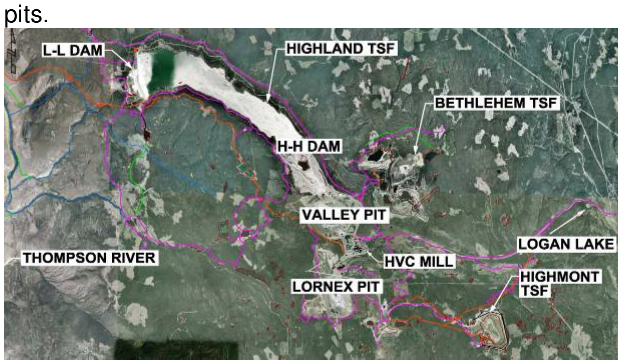

Figure 4. General Arrangement at HVC

Figure 5. L-L Dam

The normal average temperature at the site is 3.8ºC (Environment Canada 2008) with average monthly mean below zero from November to March annually. The average annual precipitation is about 350 mm with about 60% rain.

Natural borrow materials available locally include a uniform clean sand, pit run clean to dirty sand and gravel, and a silty gravelly till. The most common structural fill material used on site however is a silty sand and gravel, bouldery mine crush.

2.2 Multiplate Overpass

During September to December 2009, a multiplate overpass was constructed to provide grade separation between the main access road to the mine and a proposed haul road for loaded Cat 797B mining trucks traveling from the main open pit to a proposed rock dump (Figure 6). The multiplate arch has a 15 m span, a 6.6 m maximum clearance and is 58 m long. The fill material comprised well graded 75 mm minus sand and crushed gravel with a maximum fines content of 7% and the specified minimum density was 95% standard Proctor maximum dry density (SPMDD), as specified by the multiplate designer. A minimum E_{vd} value of 45 MPa (MN/m^2) was specified for the LWD tests.

Figure 6. Night Time Construction at the Multiplate Underpass

Due to schedule requirements, fill placement and compaction occurred during freezing weather and it was necessary to implement several cold weather precautions. These included adding geotextile reinforcement at each 200 mm lift and maintaining the backfill moisture content well below the optimum moisture content such that the material would not freeze between excavation from the stockpiles and placement and compaction. The stockpiled material and compacted fills were protected with thermal blankets until immediately before new fill placement. To avoid soil freezing overnight, construction activities were conducted continuously day and night until the fill placement was completed. If work stopped for more than a few hours, it then became necessary to strip frozen fill from the surface.

The LWD and the nuclear densometer were both used to provide quality assurance testing for the backfill (Figure 7). About 500 measurements of the dynamic soil modulus (E_{vd}) were taken using the LWD. The majority of these were performed at the same location as testing using the nuclear densometer. In a few instances the material was too coarse to test with the nuclear densometer and only E_{vd} measurements taken. This program provided a data set of E_{vd} versus percent standard Proctor compaction which allows for an examination of the relationship between the LWD dynamic bearing plate displacement (S) and the dynamic modulus (E_{vd}) and the dry density of the compacted soil. The LWD was able to identify areas with insufficient compaction, in particular close to the metal multiplate arch and wing wall retaining walls.

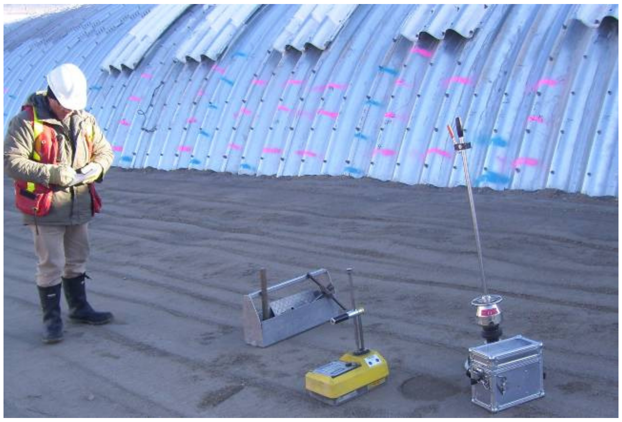

Figure 7. Quality Testing of Backfill Using the LWD and Nuclear Densometer

2.3 Coarse Ore Stockpile Covers

Three 80 m diameter coarse ore stockpiles provide feed for the Highland Mill. The stockpiles are supplied with coarse ore from the mill primary crusher by conveyor belt and ore is retrieved below the stockpiles through reclaim tunnels. The stockpiles were constructed between 1970 and 1988 with no provision for dust control which has been an issue during the operating life of the mill. As the ore drops from the conveyor belts to the top of the stockpiles, the prevailing winds carry finer particles away, creating dust plumes that result in poor visibility during high winds, accumulations of dust over buildings, roads and equipment, and mineral loss to the milling process. Dust emissions are particularly problematic during freezing weather when it was not possible to spray the ore on the conveyor belts with water to reduce dust.

To minimize dust emission, three 93 m diameter by 35 m high geodetic dome structure are being built to cover each of the three stockpiles (Figure 8). The domes were designed such that the stockpiles would remain operational during the entire construction period.

The foundations of the domes are underlain by 13 m to 25 m of loose to compact crushed ore (fill) comprising sand and gravel, cobbles and boulders and layers of fine wind-blown silt. The spread footing foundations were placed at depths greater than 5.5 m to resist uplift loading and the fill around the 750 mm diameter steel columns was compacted to a dense state to resist the large lateral loads imposed on the foundations. The fill comprised a mixture of 75 mm minus gravel and coarse ore and was placed and compacted at each foundation footing in 300 mm to 450 mm thick layers. The fill placed was selected to be free of particles larger than 150 mm in diameter and was typically well graded.

Figure 8. Construction of Coarse Ore Stockpile Dust Covers

The average measured E_{vd} of the compacted foundation soil was 58.2 MPa and E_{vd} of the backfill above and within 3 m of the footings was about 130 MPa. Due to the variable and coarse nature of the backfill material, the fill was not tested in the laboratory for gradation or maximum density and the nuclear densometer could not be used for compaction control. Quality assurance (QA) testing was carried out using the LWD (Figure 9). There were limitations on the use of the LWD, for example when the depth of excavation was such that personnel entry was not possible due to safety concerns. These limitations would have applied to most other conventional in situ testing methods, and so a method specification with visual observation program supplemented the testing. The LWD tests provided the only directly measured, repeatable and quantifiable quality assurance records.

Figure 9. Testing of Coarse Fill with the LWD

2.4 Fuel Tank Station

In August 2008, the fuel and fluids station (Lubeland) for the fleet of Cat 797B mining trucks was relocated to a waste dump on the east side of the Valley Pit. Test pitting revealed that the upper zone of the dump was coarse sand and gravel waste from open-pit mining operations with zones of organics, silt or clay. The facility includes a mining truck lubrication building, a series fuel tanks and a fuelling pad, which is built within a lined containment berm. The area was excavated to a depth of 3 m and backfilled and compacted to 98% standard Proctor density using three inch minus crush rock in maximum 300 mm lifts and a vibratory roller.

Every lift was tested for compaction using the LWD tester and, where practicable, the nuclear densometer. The addition of oversize (up to 75 mm) material resulted in rock contents greater than 20% and appropriate results could not be always be obtained from laboratory standard Proctor testing of the sand and gravel / crush rock mixture. The LWD was useful in compaction control where the nuclear densometer could not be used.

2.5 L-L Dam

The L-L Dam has been raised annually since the late 1970's by 1 m to 4 m, by the centreline method, to accommodate tailings storage. The current maximum height of the dam is about 150 m. The dam comprises an underlying sand and gravel drainage blanket, with a downstream cycloned sand embankment, a 15 m wide till core and an upstream cycloned sand embankment berm (Figure 5).

The main embankments are constructed using cyclone sand. Whole tailings are run through a cyclone house and the coarser sandy underflow is sent to a series of prepared cells across the dam. Water is forced out of the sand by track packing with a bulldozer and drained from the cells. The wet track-packing and draining provide compaction meeting or exceeding the requirement of 97% standard Proctor density. During the spring and early summer of 2008, the LWD tester was used side-by-side with the nuclear densometer (Figure 10) to provide a database of the relationship between the LWD dynamic bearing plate displacement (S) and the dynamic modulus (E_{vd}) and the dry density of this compacted sand.

Figure 10. Testing of Hydraulically Placed Cycloned Sand with the Nuclear Gauge

3 TEST RESULTS

3.1 Multiplate Overpass

We examined the relationship between the LWD displacement (S) and the dynamic modulus (E_{vd}) versus the dry density of the soil by comparing data from the LWD versus the nuclear densometer tests at the multiplate overpass. The plot of dry density versus deflection is shown in Figure 11 and the plot of dry density (expressed as a percentage of standard Proctor density) versus dynamic modulus is shown on Figure 12. Trend lines on these figures show an increase in stiffness with increasing soil density, i.e. lower deflection and higher dynamic modulus for denser material.

There is a very large scatter in the data as described by the low correlation factors of the linear trend lines shown on the figures. It may be possible to reduce some of the scatter by removing points where density measurements are less reliable (e.g. where the density tests were done at a distance of less than 1.5 m from the edge of the retaining walls or the edge of the multiplate steel arch, or where large oversize particles were within the testing zone). In addition the data has not been screened for varying material gradation and we expect that by grouping material of similar coarse rock oversize percentages, better correlations would emerge. Due to the time pressures during construction, it was not possible to obtain more accurate rock oversize estimates at all 500 test locations. This type of data acquisition is typical of research projects, but is not suitable for construction QA monitoring as the increased detailed monitoring would cause a significant delay in construction.

The results confirm the usefulness of the LWD as a general QA check of the nuclear densometer derived density test results.

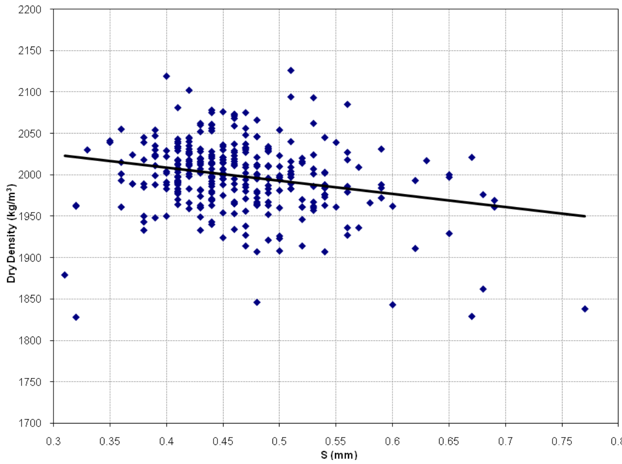

Figure 11. Multiplate - Dry Density versus Deflection

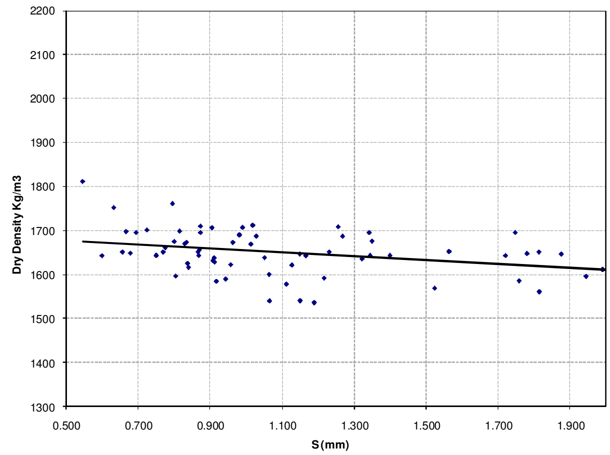

Figure 13. L-L Dam - Dry Density versus Deflection

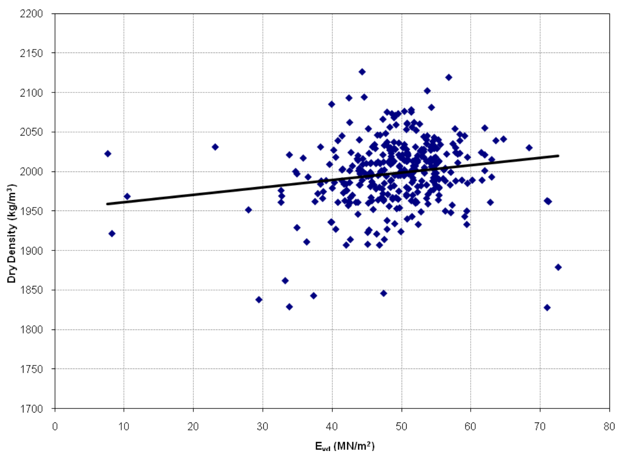

Figure 12. Multiplate – Dry Density versus Dynamic Modulus

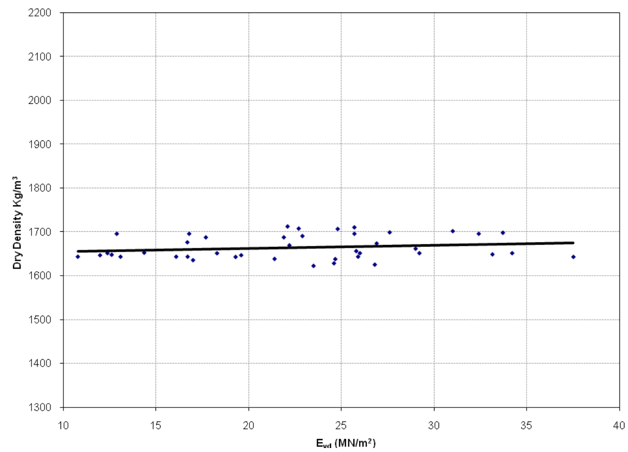

Figure 14. L-L Dam - Dry Density versus Dynamic Modulus

3.2 L-L Dam Cycloned Sand

Cycloned sand is tested regularly using a nuclear densometer for QA. As the fill zones are extremely large and there is a large variation in the sand gradation depending on mill feed quality it is necessary to repeat standard Proctor tests at least at weekly intervals for quality assurance.

We examined the relationship between the dry density of the soil and the LWD dynamic bearing plate displacement (S) and the dynamic modulus (E_{vd}). The plot dry density versus deflection is shown in Figure 13 and the plot of dry density versus dynamic modulus is shown on Figure 14. The trend lines, similar to those on Figures 11 and 12, show that denser soils are stiffer with lower deflection and higher dynamic modulus. Due to the greater uniformity of the tested sand at L-L Dam, compared to the coarse and variable waste rock fill at the ore stockpile site, the relationships have much lower variability and a stronger correlation is evident.

4 CONCLUSIONS

Figure 15 presents a summary of results from both the multiplate site and the L-L Dam site for dry density versus dynamic modulus. This combined trend line confirms that as the density increases the dynamic modulus of the soil increases. Despite the significant scatter in the data, there is a clear trend. We have not taken the extra step of filtering the data points, and this data includes points with significant variation in material type (oversize, moisture content, uniformity). Further analysis of the data would likely reduce the scatter.

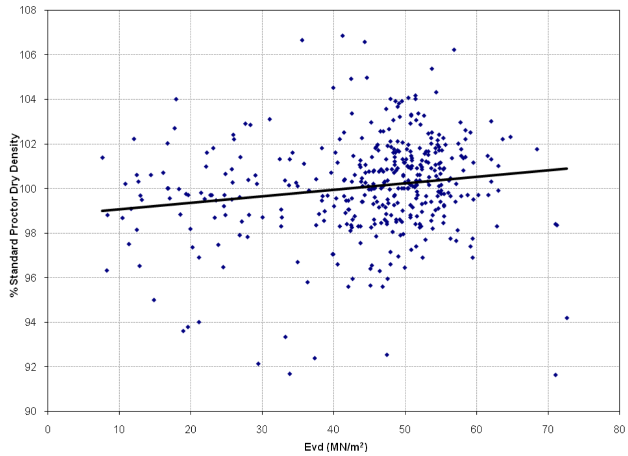

Figure 15. All Data – Dry Density versus Dynamic Modulus

Throughout its use at numerous projects at HVC, the LWD has proven to be a valuable aid in the testing of compacted backfill:

- Test results have been proven to be repeatable;
- The LWD can be used in gravelly and cobbly soils, where the nuclear densometer cannot;
- As the depth of influence of the LWD is 1.5 to 2 times the plate diameter, the LWD provides information of deeper zones;
- The correlation of E_{vd} to dry density on a per site basis is considered adequate for the purpose of quality control testing; and
- Stronger correlations are possible for more uniform soils.

The results from both the L-L Dam and the Multiplate Overpass sites confirm a relationship and loose correlation between increasing stiffness and E_{vd} with increasing density. At this point, we caution that any specific correlation should be derived for each specific site under the given site conditions and considering the moisture content and gradation of the fill material. Nevertheless, the LWD provides, through measurements of stiffness and dynamic modulus of elasticity, a direct indication of the density and an indirect measure of the strength of compacted fills.

Since the start of construction season in 2008 the LWD has been in constant use at HVC with only minor repair and general servicing and we consider this instrument to be robust and reliable. The following drawbacks were identified:

- The LWD is not in common distribution in Canada and must be sent overseas to be calibrated and for major servicing, although, it was found that minor repairs to the electronics were easily fixed locally; and
- The instrument was found to respond sporadically at temperatures less than -20°C.

Future work at HVC will include gathering additional test data and further development of site specific relationships between standard Proctor density and dynamic modulus. A test section with controlled compactive effort is also being considered.

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