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# Embankment Compaction and Quality Control at James Bay Hydroelectric Development

J.-JACQUES PARE, BERNARD BONCOMPAIN, JEAN-MARIE KONRAD, AND NARENDRA S. VERMA

**Construction of 220 dams and dykes at the La Grande Complex, James Bay hydroelectric development involves several types of materials (till, sand and gravel, and rockfill) and construction procedures and equipment that must yield embankment zones of desired characteristics. Experience and design requirements, as well as the schedules, economic, and climatic restraints, have led to a general standardization of the specified material placement techniques and conditions. This paper deals with some of the practical aspects of the specifications that are developed with a suitable balance between the procedure and product specifications and reviews the relative importance placed on visual inspections and various control and verification tests. The difficulties encountered with the quality control and verification testing procedures are discussed and comments are made regarding the relative accuracy and suitability of these tests. Typical properties of the embankment materials based on extensive tests carried out on 160 Mm$^3$ of materials are also included.**

The La Grande Complex (phase 1) of the James Bay hydroelectric development involves construction of about 220 earth and rockfill embankment dams and dykes that have a maximum height of 160 m. The complex covers a territory about 800 km long and 400 km wide and is located about 1000 km from Montreal in northern Quebec (Figure 1). Construction of these embankments at the five main project sites, namely La Grande 2 (LG2), LG3, LG4, Eastmain-Opinaca (EOL), and Caniapiscau, began in 1973 and is scheduled to be completed in 1982. The work procedures specifications and the quality control requirements and methods have been developed from the experience acquired at the Manicouagan-Outardes Project in Quebec and the Churchill Falls Project in Labrador, with almost similar geological and climatic conditions.

## PROJECT DESCRIPTION

The complex lies within the Canadian Shield, a glaciated peneplain developed on a precambrian basement complex of igneous and metamorphic rocks (1). The project sites are underlain mostly by granitic rocks that range in texture from massive to gneissic. Glacial and fluvio-glacial sediments cover some 80 percent of the region. Glacial till is widespread in the form of ground moraine, locally including some drumlin deposits, and forms an excellent source of impervious material for embankment construction. Eskers and kames constitute the principal source of granular materials for filters, transitions, and shells. Sensitive marine clay and peat deposits blanket some of the western limits of the area.

The climate is characterized by low temperatures with a mean annual temperature of -4°C. No permafrost has been encountered, although the Geological Survey of Canada maps show that the complex is located within the sporadic permafrost zone. Frost penetration of up to 3 and 9 m has been observed in till deposits and bedrock, respectively (2). Till placement under nonfreezing conditions is limited to about 150 days between May and October. Rainfall during this period, which corresponds to about 65 percent of the total annual precipitation, ranges from about 400 mm at LG2 to about 500 mm at Caniapiscau.

## Typical Embankment Characteristics

The construction of the 220 dams and dykes with a total crest length of approximately 130 km involves about 30 Mm³ of till, 60 Mm³ of natural granular material or crushed aggregate, and 70 Mm³ of rockfill. These materials are used in embankments with three principal types of design sections (3), namely rockfill, granular, and homogeneous. The choice of the type is dictated primarily by the material available, the height of embankment, and the foundation conditions.

As a result of well-organized construction facilities, high rates of fill placement (average of more than 1 Mm³/week at La Grande complex) have been realized despite the difficult placement conditions (4). Typical rates of fill placement in a dam or dyke are summarized as follows:

1. Till core--30 000 m³/week average, maximum of 120 000 m³/week at LG2 main dam;
2. Filter and transition--15 000 m³/week average, maximum of 40 000 m³/week at LG4 main dam;
3. Granular shell--90 000 m³/week average, maximum of 240 000 m³/week at Dyke QA8 at LG4; and
4. Rockfill shell--130 000 m³/week average, maximum of 450 000 m³/week at LG2 main dam.

## Specifications

Although the embankment construction specifications are prepared individually for each contract to take into account the specific design and construction conditions of the project involved, a general standardization has been achieved so that they vary only slightly between different projects. The specifications have been developed along the following lines:

1. Designation of borrow areas,
2. Product specifications for materials, and
3. Procedure specifications for fill placement.

Tables 1 and 2 and Figure 2 present a summary of specifications for the principal construction mate-

**Figure 1. Location of project sites.**

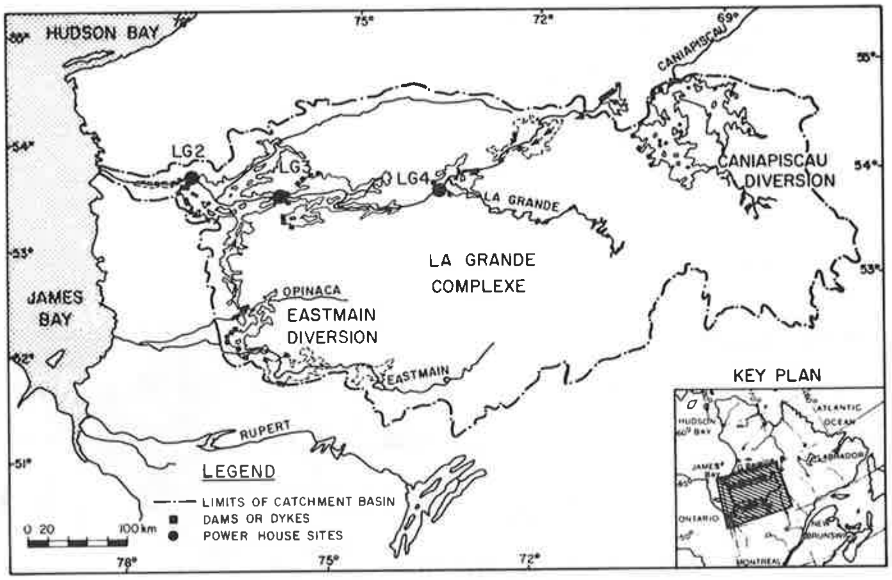


**Table 1. Summary of material specifications.**

| Item | Core and Impervious Shell | Filter, Transition, and Granular Shell | Rockfill |
|---|---|---|---|
| Equipment and method | General–selected extraction according to borrow pit conditions, removal of particles > 2/3 of compaction lift thickness, and stripping of organic and weathered materials<br>Wet material–drainage of ground and surface water, extraction on long and shallow faces, and rotary kiln drying<br>Cold weather–use of unfrozen material and use of heated haul trucks | Stripping and drainage, selective extraction, screening, crushing, mixing, washing, and extraction along high faces | Controlled blasting and removal of particles larger than the lift thickness |
| Product | Within specified gradation envelopes (Figure 4); $w > (w_{opt} - 1$ percent), $w \leqslant w_{rut}$ or ($w_{opt}$ + 2 percent), $W_{rut}$ = water content for which 45-Mg pneumatic roller produces ruts that exceed 15-cm depth in fill surface | Within specified gradation envelopes; Figure 4 for filters and transitions, Figure 7 for pit-run material | Maximum size = lift thickness; less than 5 percent passes No. 200 sieve |

rials used in the embankments.

## Quality Control

Quality control includes both visual inspection and laboratory testing of materials at the borrow areas as well as on the fill. Visual inspection to control material, equipment, procedure, and product is of utmost importance because it permits a rapid and general evaluation of the quality of work, particularly of the embankment homogeneity. Survey crews and field laboratories provide the necessary technical support to the inspection units.

Three categories of tests are performed:

1. Grain-size analyses and water content determination (carried out at a rate of about 1/5000 $m^3$ or 1/day and 1/1000 $m^3$, respectively) for a quick verification of the conformity of materials to specifications;

**Table 2. Summary of embankment construction specifications.**

| Item | Core and Impervious Shell | Filter, Transition, and Granular Shell | Rockfill |
|---|---|---|---|
| Geometry | | | |
| Lift thickness | 45 cm | 45 cm | 90 cm for interior zone, 180 cm for exterior zone |
| Construction tolerance | ±30 cm with respect to design lines | ±30 cm | ±30 cm |
| Equipment | Pneumatic roller—weight, 45 Mg; loading box for each wheel working independently; tire pressure, 550-650 kPa; operating speed, 5 km/h | Light vibratory roller—weight, 3600 kg, frequency, 1600 rpm; centrifugal force; 90 KN; and operating speed, 5 km/h | Heavy vibratory roller—weight, 9000 kg; frequency, 1200 rpm; centrifugal force, 150 KN; and operating speed, 5 km/h |
| Passes | | | |
| Number | 4 | 4 for light roller, 3 for heavy roller | 4 |
| Overlap | 25 percent | 25 percent | 25 percent |
| Required fill density, not specified | 90 percent of results > 97 percent of standard Proctor maximum density; 100 percent of results > 95 percent $\gamma_{max}$ | 90 percent of results > 70 percent relative density or 95 percent of maximum target density; 100 percent of results > 65 percent relative density or 90 percent of maximum target density | None |
| Payment | By $m^3$ of material placed, including extraction, processing, transport, handling, and compaction; for additional compaction by hour when required density is not obtained by specified procedure; and lump sum for kiln drying and winter protection | Same as for core | Same as for core |

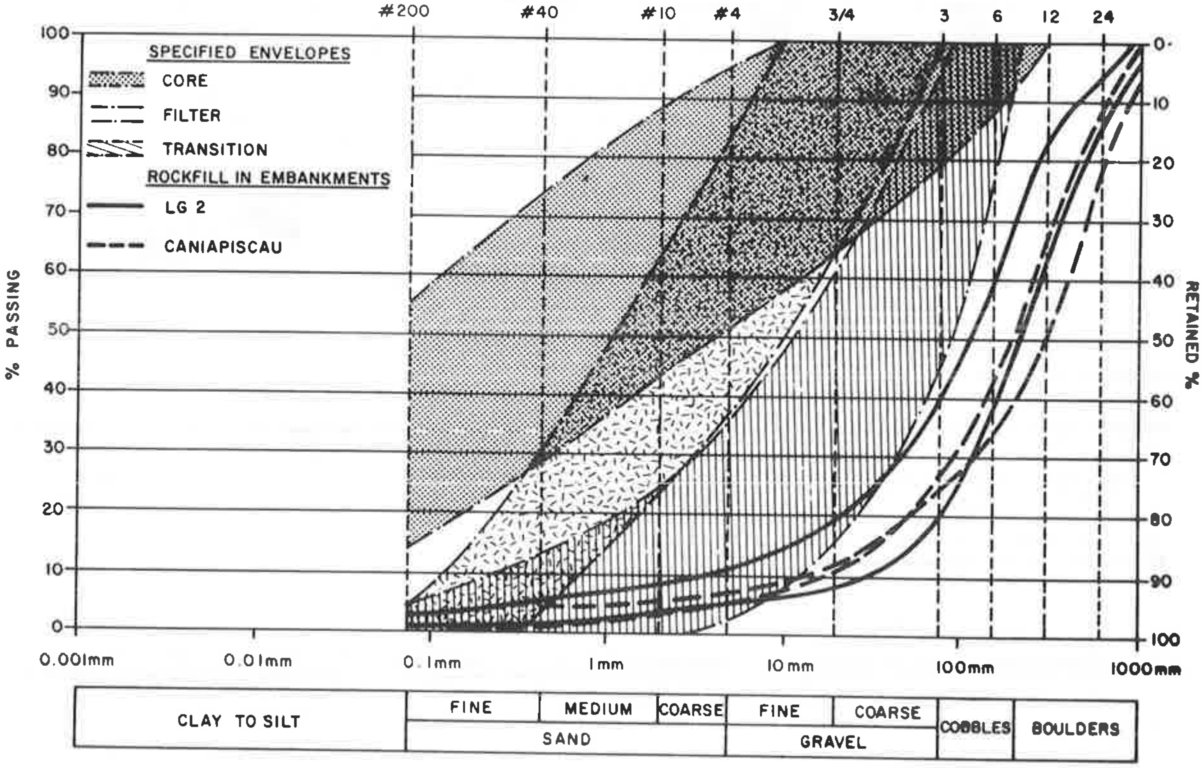


**Figure 2. Gradation specifications.**

2. Measurement of field densities and reference or target densities on a regular basis with a frequency of about 1/5000 $m^3$ or 1/day to monitor uniformity of fill placement; and
3. Determination of permeability, compressibility, and strength characteristics of the embankment materials, carried out annually to verify the conformity of the material properties with the design assumptions.

## TILL

The till encountered at the La Grande Complex and used for the impervious zones is generally a nonplastic, well-graded silty sand and gravel material with cobbles and boulders (Figures 2-4). This material is easy to compact when it is not too wet and provides a compacted fill of adequate imperviousness ($k = 10^{-5}$ to $10^{-7}$ cm/s). The main construction problems to be tackled during borrow pit exploitation and placement of the till are related to the presence of the oversize boulders, the natural variations in water content, and the susceptibility to frost.

### Material Selection

Selective extraction, based on visual inspection, in the borrow area is the first step to obtain material of desired gradation characteristics. Oversize boulders are eliminated at the borrow areas by putting them aside in stockpiles or by means of grizzly- or kolman-type separators and on the embankment by passing a rake through the lifts. Such scalping on the embankment surfaces, although permitted in the technical specifications, is not encouraged due to the likelihood of segregation and contamination of the adjacent zones. Figure 3 shows two gradation envelopes for the same material for a given site, one as it existed in the borrow area and the other as placed in the embankment. It demonstrates the effectiveness of these control and processes.

The water content in the borrow pits is variable. The commonly encountered and maximum variations of the natural water content with respect to the standard Proctor optimum water content is about 2-3 percent and 5 percent, respectively. Water content of the wet material was adjusted at the borrow pit by suitable surface drainage, proper excavation techniques, and stockpiling to facilitate drainage and aeration. Watering on the embankment is also employed occasionally.

Kiln dryers have been used successfully when needed to meet the high production rate requirement or in the case of wet borrow areas. Use of such a plant allows fill placement during rainy or cold periods and extends the construction period by about 50 days. The rate of material processing that corresponds to a moisture content reduction of about 2-3 percent was about 450 Mg/h--the energy consumption increases with the required change in moisture content.

In view of the need to use heavy haul trucks to meet construction schedules and based on a detailed program for testing equipment performance, the 45-ton rubber-tired rollers were used with four independent loading boxes. This choice has proven to be satisfactory and has ensured better compaction for till with a relatively high percentage of boulders and cobbles and with moisture content generally above the optimum value.

Specifications permit neither the placement of frozen material in the core nor the placement of till on frozen surfaces. Protection against frost is therefore required to minimize the volume of frozen fill that must be excavated and thus allow a rapid resumption of work in the spring. Such protection has been obtained by placement of a 3-m thick layer of granular material, a 2-m thick layer of manufactured snow, or an appropriate combination. The first method is particularly suitable for dykes that have granular shoulder zones where protection material can be reused in the embankment.

### Visual Inspection

The main items on which the visual inspection efforts were concentrated are as follows:

1. Material quality and presence of contaminants;
2. Material gradation and homogeneity;
3. Water content, presence of wet spots, and ruts;
4. Condition at interfaces of embankment zones;
5. Roller type, weight, speed, and tire pressure;
6. Placement, lift thickness, number of passes, and overlap between passes; and
7. Ambiant climatic conditions.

### Material Control Tests

The determination of water content has been performed either by 18-h oven drying as per ASTM D2216-71 or by rapid drying (20 min) in a microwave oven or in a moisture teller apparatus. Both methods have provided identical results. The speedy moisture tester and the nucleodensitometer did not give satisfactory results compared with those of the oven-drying method and have not been employed. In order to achieve a procedural uniformity that permits a valid comparison between samples from borrow area or fill and between tests for natural and optimum values, the testing of moisture content has been carried out on a specified fraction of the material (fraction smaller than the gravel size). Analyses of grain size distribution have been performed in the laboratory by sieve and hydrometer analyses after removal of boulder and cobble sizes on the fill.

### Compaction Control Tests

Evaluation of the material compactness and homogeneity has been based on a comparison of the field dry density with the maximum Proctor density corrected for the gravel content of the sample as per relationship developed by the U.S. Bureau of Reclamation (E-38) Earth Manual 1974.

#### In Situ Density

Two procedures, the sand cone and the nucleodensitometer, have been used to measure the field densities. At the early stages of construction at LG2 and EOL, although both procedures were employed simultaneously, confidence was placed in the results of the sand-cone test. The nucleodensitometer densities were corrected based on the results of parallel testing done by these two methods, such as shown on Figure 5. Progressively with experience, due confidence was placed on the results of the tests by nucleodensitometers that were regularly calibrated.

The collective experience gained at all project sites over the years has shown that numerous factors, in addition to those considered in the testing standards, influence the accuracy of the results of both types of tests. Thus, the results of the sand-cone test are prone to errors due to cone volume changes in a wet material and to the vibrations generated by the nearby construction operations. Similarly, the nucleodensitometer results are influenced by depth of probe penetration and by the presence of cobbles within the energy flux field and the accuracy of the apparatus that may be sensitive to field conditions. Nevertheless, the nucleodensitometer has proven to be a quick and reliable apparatus for field-density measurements provided its calibration is checked regularly and four measurements in the crosswire positions are made with a probe penetration of 20 cm for each test.

### Maximum Density and Optimum Water Content

The optimum water contents and the maximum dry den-

Figure 3. Till gradation in borrow pits and as placed in embankments.

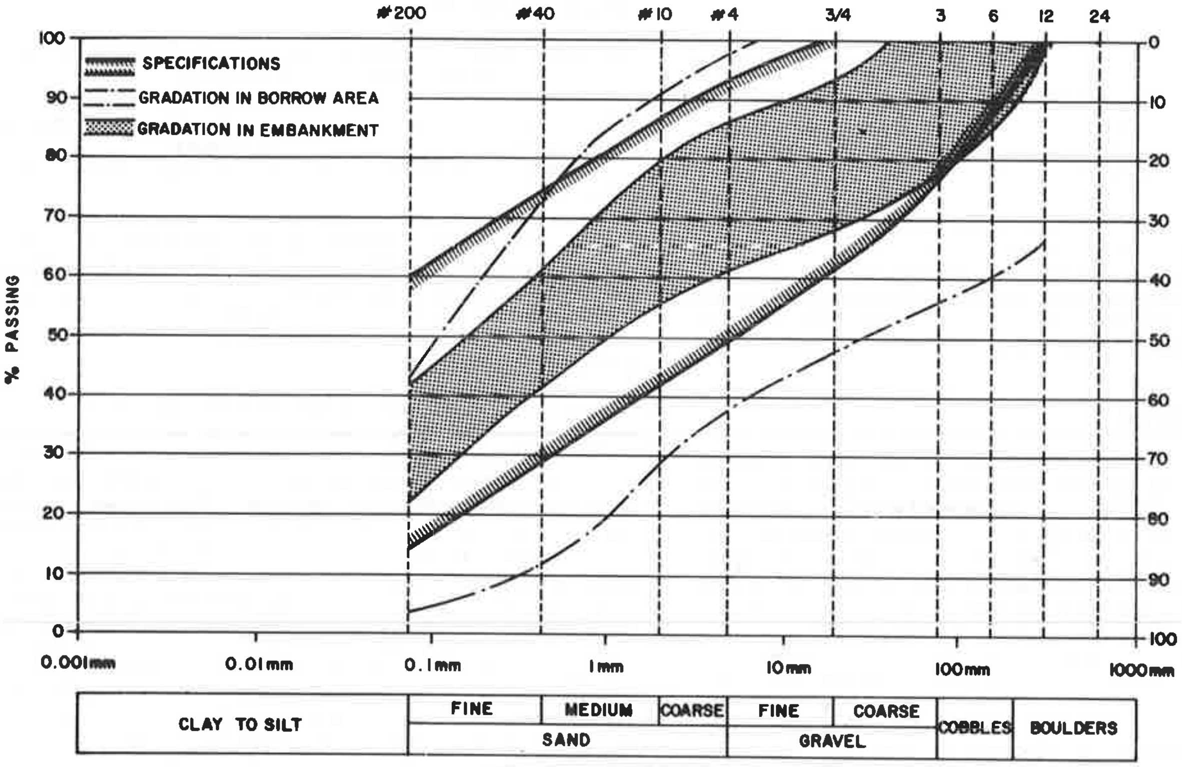
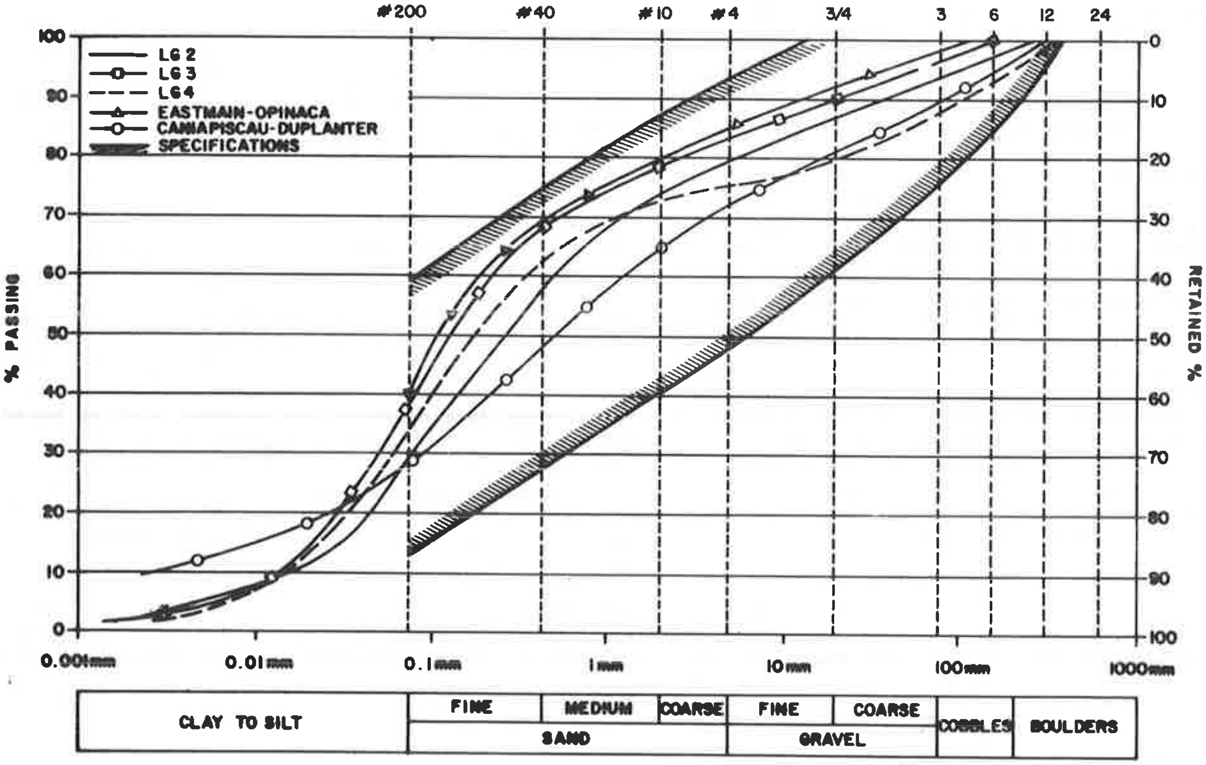


Figure 4. Mean gradation of placed till at different sites.



sities have been determined according to ASTM D698-70, A or D. Whereas the method A tests are easier and faster to perform, the method D tests are considered to be better suited to the overall gradation of the material. Table 3 and Figure 6 present a comparison of the method A results corrected for coarse fractions with the corresponding results determined in a large rigid box or by method D. These tests have demonstrated that both method D and method A (when duly corrected for the coarse fraction) as used for the till with oversize fractions not exceeding 30 percent of the total volume gave results that were considered to be in good agreement with reality. Some rapid estimation methods that involve relations between gradation characteristics and maximum density have also been developed in order to complement the standard Proctor tests.

The maximum dry density varies between 2.0 and 2.2 Mg/m³ and the corresponding optimum water content varies between 7.3 and 8.2 percent. The fill densities correspond to about 97 to 99 percent (percentage compaction) of the standard Proctor maximum density at LG3, LG4, and Caniapiscau. Somewhat high average compactions (99-100 percent) were observed at LG2 and EOL and are attributed to an overestimate of the in situ density determined by the sand-cone method.

## GRANULAR MATERIAL

The specified gradation limits for the shell zones are well adapted to the broad range, which varies from uniform fine sands to coarse gravels, in the borrow areas. The material processing limited to scalping of the boulders of sizes in excess of 30 cm and to elimination of the zones of fine sand concentration has been adequate and satisfactory.

The granular materials used in the filter and transition zones required selective exploitation of borrow pits or special processing in order to meet the following filter design criteria (where B and F correspond to the base and filter materials, respectively):

1. $D_{15F} \geq 5D_{15B}$,
2. $D_{15F} \leq 5D_{85B}$,
3. Less than 5 percent of the filter material passes sieve no. 200, and
4. Parallelism of the gradation curves of both materials.

The gradation of the filter zones is designed with respect to the gradation of the till matrix (i.e., the fraction that passes sieve no. 4, which in fact is the material to be protected against erosion). Processing of sand and gravel deposits was performed when needed to produce material that meets these filter criteria, including screening, crushing, and mixing, while erecting stockpiles at the borrow pits. Typical gradation curves for a filter material as it existed in the borrow pit and as placed in the embankment are shown in Figure 7.

Since the sand and gravel deposits are relatively heterogeneous, a selective exploitation was employed to minimize the processing and maximize the homogeneity of the fill material. Segregation in the stockpiles was also significantly reduced by erecting stockpiles of limited height in layers less than 1-m thick. Gradation analyses are carried out on a regular basis before and after treatment of the material at the borrow pits, in the stockpiles, and on the embankments.

### Placement

The construction problems encountered during the placement of the granular materials were generally related to segregation, contamination, and over com-

**Figure 5. Comparison of till densities determined by sand cone and nucleodensitometer.**

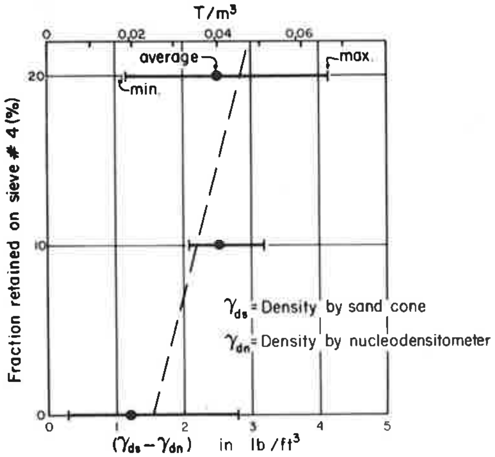


**Figure 6. Accuracy of standard Proctor method A densities.**

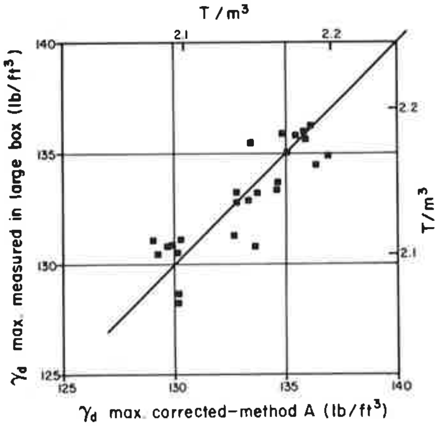
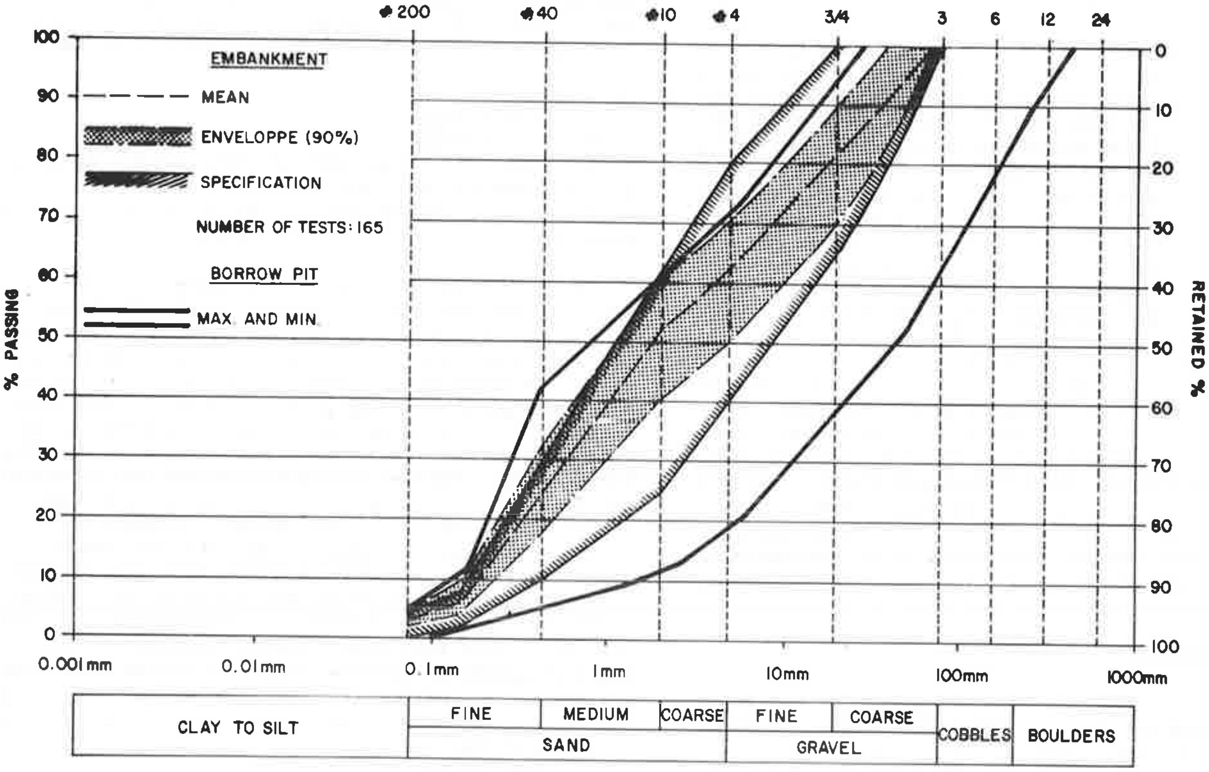


**Table 3. Comparison between standard Proctor methods D and A with oversize gravel correction.**

| Site | Borrow Area | No. of Tests | | Fraction Smaller Than | | $\gamma_d$ max Method A (Mg/m³) | $\gamma_d$ max (A) Corrected (Mg/m³) | $\gamma_d$ max Method D (Mg/m³) | $w_{opt}$ Method A (%) | $w_{opt}$ Method D (%) |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Method A | Method D | 19 mm | 4.8 mm[a] | | | | | |
| LG 2 | G and J | 470 | 164 | 93 | 86 | 2.07 | 2.11 | 2.12 | 7.6 | 6.7 |
| Caniapiscau | A2 | 20 | 20 | 96 | 88 | 2.11 | 2.15 | 2.16 | 7.8 | 7.5 |
| | A1 | 4 | 17 | 91 | 82 | 2.12 | 2.16 | 2.16 | 8.0 | 7.6 |
| | A8 | 8 | 20 | 90 | 80 | 2.18 | 2.21 | 2.19 | 7.5 | 6.9 |

Note: The results presented above represent average values based on tests carried out on materials of relatively similar gradation characteristics for each borrow area.
[a] Sieve no. 4.

Figure 7. Gradation filter material in borrow pits and embankment, dike TA-24 - LG 3.



paction. Segregation that creates conditions conducive to internal erosion and piping has been curbed by limiting the maximum particle size to 75 mm in the filters and to 150 mm in the transitions, by pushing with grader blades the coarse fractions toward the outer limits of the zones, and by raking at the zone interface to produce progressively changing material.

In order to limit the contamination of the filter and transition zones with the till from the adjacent core due to traffic or due to washing during rainfall, the placement of the filter material with one layer in advance of the core material was adopted and has proven to be effective. The problem of over compaction, which is a result of the shape, size, and well-graded nature of the material rendering it easy to compact, has been handled by reducing the number of passes of the vibratory rollers by one and by restricting construction traffic over these zones.

## Quality Control

Quality control for the granular materials involves visual inspection, which is aided and complemented with laboratory testing and surveying. The homogeneity of the fill is examined occasionally by excavations of trenches. Visual inspection is directed at controlling

1. Gradation with rapid determinations of the fraction that passes the no. 200 sieve,
2. Lift thickness,
3. Water content (wetting of the lift may be necessary), and
4. Number of passes, overlap, speed, and frequency of vibration of the rollers.

Testing is performed to determine the gradation characteristics, the in situ density of fill, and the corresponding maximum-minimum of a target maximum density. The in situ densities are measured by the water replacement method (by using 0.4 m and 1.3 m diameter rings for the filter and transition zones, respectively) or with a nuclear device. Based on the experience of the Société d'énergie de la Baie James as well as that of others (5), the results of relative density tests are prone to significant variations due to slight variations in testing procedures and materials. Thus, whereas this method was found to be satisfactory for relatively homogeneous materials of filter zones, its use for the shell materials that have a significantly wide range of gradation characteristics was considered unsatisfactory. The use of relative compaction (in situ density expressed as a percentage of a target density for material of similar gradation) has been found to be more suitable and has been employed for shell zones.

Target density represents the average of the upper 10 percent of a large number of density measurements and was determined with respect to the percentage of material that passes sieve no. 4. The empirical relation between the target density and the percentage of gravel fraction, as developed at LG4, is shown in Figure 8. A density that corresponds to 95 percent of the target density has been found to be equivalent to a relative density of about 70 percent.

Comparative tests were performed on the filter material at LG3 to ascertain the relative accuracy of the in situ density testing with a 0.5-m diameter ring and with the nuclear device by using four cross-wire reading positions and the probe lowered to 25-cm depth. As shown in Figure 9, densities obtained from the water replacement method are generally higher than those given by the nucleodensitometer, the difference increasing with density. Further investigations carried out on material of known

**Figure 8. Embankment dry density (maximum 10 percent) versus percentage gravel.**

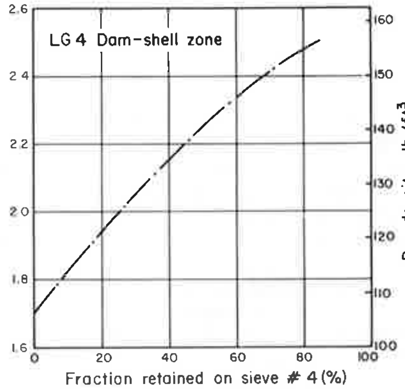
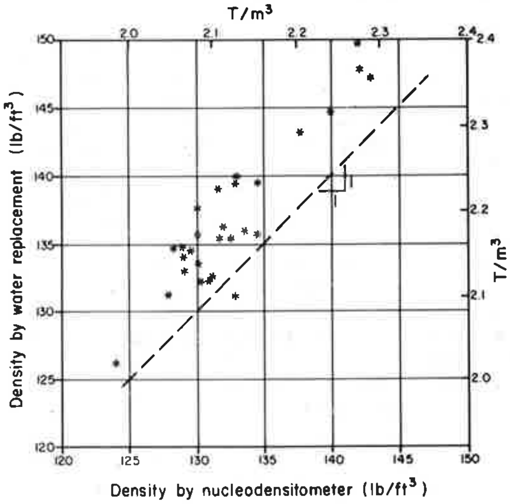


**Figure 9. Comparison of water replacement and nucleodensitometer methods.**



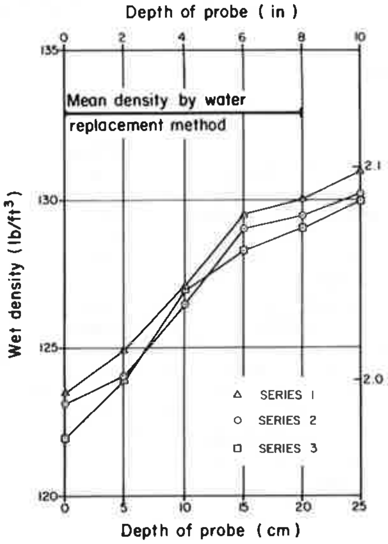
density (placed in a rigid box) showed that the wet density measured with the nuclear device increased with increasing depth of the probe up to a depth of 15 cm, and the variation diminished thereafter (Figure 10). Studies carried out in a test box revealed that, for a pit-run granular material, the mean density deduced from the water replacement method is approximately 1-2 percent higher than density based on direct measurements of the weight and size of the box. The use of the nuclear device with the probe lowered to 15 cm or more is thus considered a satisfactory method for rapid evaluation of the in situ density of granular material provided the results obtained are calibrated against the water replacement method.

Following the specified compaction procedures and this new approach of compaction evaluation, the granular materials at different project sites have been found to be at 95-97 percent relative compaction (2.0-2.2 Mg/m³). Statistical analyses for the transition material has shown that the specified compaction with heavy vibratory rollers (10 Mg, 3 passes) produces good results with a density of about 2.30 Mg/m³.

## ROCKFILL

In addition to the visual inspection of particle sizes, lift thicknesses, and number of passes of the 10-Mg vibratory rollers, quality control of the rockfill shell zones involved occasional measurement of the in situ density by the water replacement method in large-scale test pits and the determination of the distribution of grain size of the material excavated from these pits. Roller effectiveness tests were sometimes performed by measuring surface settlement with respect to the number of passes. The results of grain size analyses performed at LG2 and Caniapiscau are shown in Figure 2. In situ dry densities of 2.24 and 2.16 Mg/m³ were measured at LG2 and Caniapiscau, respectively.

**Figure 10. Density variation with depth of nucleodensitometer probe.**



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