Measurement of In-Place Relative Density in Coarse Grained Alluvium for Comparison to Penetration Tests

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Introduction

This paper summarizes results of investigations into coarse grained alluvial soils at several Bureau of Reclamation dams. In-place density tests have been performed in coarse grained deposits to measure relative density. Relative density data can be correlated to liquefaction resistance and to penetration testing. Penetration tests are the primary method of determining liquefaction resistance.

Relative Density Measurement Methods

Geotechnical engineers describe the compactness of sand and gravel soils with few fines in terms of "Relative Density." These tests have been standardized by The American Society for Testing and Materials (ASTM) (*1*). Reclamation was involved in the development of these ASTM standards, and Reclamation's procedures (*2*) are in accordance with ASTM standards. Relative Density, D_d, is expressed in terms of void ratio, e, as:

$$D_d = e(max) - e\ (in\text{-}place) / e\ (max) - e\ (min) \qquad \text{Eqn (1)}$$

Using relative density as an indicator of sand condition, geotechnical engineers have performed many research studies of sand behavior by placing sands at differing relative densities. By measuring the in-place density of alluvium and determining its relative density, a judgment can be made as to whether the soil is potentially liquefiable in earthquake shaking. Determining relative density is not without problems. It was the topic of a large ASTM symposium in 1971 (*3*). This symposium summarized significant experiences with measurement of relative density from in-place density measurements, from penetration testing, and from the test laboratory procedure itself.

Relative Density and Penetration Resistance

There are many problems with estimating relative density from penetration tests. The SPT has mechanical and operator variations which cause variable energy transmission to the penetrometer(*4*). There also can be errors in SPT because of drilling disturbance. Tests from coarse sands give slightly higher blow count values than test in finer sands, and tests in gravels are frequently unreliable. Gibbs and Holtz performed the first chamber tests of sands with SPT (*5*). These chamber tests were then reproduced 20 years later by Marcuson and Bieganousky of the U.S. Army Corps of Engineers (*6*, *7*). Chamber testing indicates that at a constant relative density, penetration resistance increases with increasing confining pressures.

Seed and Idriss (8) published a proposed relationship between relative density and liquefaction resistance. Their work related penetration resistance from case histories of liquefaction at field sites to relative density using the chamber test relationships for sands. Sands with relative densities of less than 50% are highly susceptible to liquefaction with large shear strain development, while sands with relative densities of over 80% may not even liquefy, or if they do, shear strains are limited. The SPT test has since been proven to be a reliable indicator of liquefaction resistance of sands without gravels, and current methods rely on direct correlation of SPT or cone penetration tests at case history sites. Methods to determine the SPT N_{160} for liquefaction resistance have been standardized by ASTM D 6066 (*1*).

In the 1990's, the Becker Penetration Test (BPT) was used in an attempt to equate equivalent SPT N values in coarser, gravelly deposits. Correlation of BPT data to relative density has even more uncertainty. This is because the correlation of BPT to SPT has uncertainty. Further, there have never been controlled tests of the BPT in soils of differing known densities. The BPT is also influenced by variables such as casing friction and particle size. For this paper, it will be assumed that the corrected Becker N_{60} value is equivalent to the SPT N_{60} values.

Methods for Accessible Measurements of Relative Density in Alluvial Materials

In-place density is determined using large scale sand replacement or water replacement methods (ASTM D 1556, 4914, and 5030) (*1*). Reclamation has had success with large sand cones. Contrary to construction control testing, large devices are not always needed. Alluvial deposits can contain thin liquefiable layers only 0.05 to 0.1 m (5- to 6 in) thick. Large frames or ring tests will often result in mixing of thin layers.

Relative density is determined in strict accordance with ASTM procedures for determining the maximum and minimum index densities (D 4253 and 4254). Vibratory tables must be carefully calibrated. The control fraction for testing is based on the minus 75 mm (3 in) size range. For any sample that has over 30% oversize, errors begin to occur and complicated corrections are needed. See studies by Donaghe and Torrey for more information on these corrections(*9*).

Access must be provided to take the in-place density measurements. Large diameter shafts have been used below the water table, and de-watering systems are often required. In many cases, exposures of gravels may be accessible near the site of interest, alleviating the need for de-watering. De-watering in cohesionless sands and gravels may result in slight compression of the materials. In large excavations, the water table must be monitored effectively, and the heavy equipment must not be allowed to “pump” the fill. In general the water table should be held 1.5 m (5 ft) lower than the operating equipment. Tests should be taken 1.1 to 1.5 m (4 to 5 ft) below the ground to minimize densification caused by heavy equipment. The walls of the excavations can be benched back 3 to 5 m (10 to 15 ft) for access.

Previous Experience With In-Place Relative Density Measurements

Reclamation routinely measures relative density of alluvial deposits in investigations for pipelines. A wide variety of relative density values for in-place natural alluvial deposits has been observed by Reclamation engineers. Overall, most natural, young alluviums fall in the range of 40 to 60% relative density. Often, values of less than theoretical zero can be obtained if the layers are mixed.

Poulos and Hed took numerous relative densities of hydraulic fill soils and found relative densities to average 50% with a range of 40 to 60% (*3*). They further estimated that the relative compaction ranged from 89 to 90%. Bell and Singh measured relative density of alluvial sands by in-place density and by penetration resistance and found a range of 25 to 45% (*3*). The Army Corps of Engineers performed large (1.2 m) diameter water replacement density tests in the foundation gravels of Mormon Island Auxiliary Dam (*10*). These gravels were placed during dredging operations. The relative density range of this dredger spoil was about 20 to 60%. Based on these data and other penetration resistance measurements, modifications were performed to Mormon Island Auxiliary Dam.

Reclamation's Test Results

Jackson Lake Dam

At Jackson Lake Dam, Reclamation used 20 cm (8 in) sand cones in 1.2 m (4 ft) diameter accessible shafts to measure the in-place relative density of a 75 mm (3 in) minus hydraulic fill embankment (*11*). The soils were primarily Poorly Graded Gravels (GP-GM) with about 60% gravel. Figure 1 shows the results of the in-place density testing. The hydraulic fill ranged from 45 to 60% relative density. Two samples had relative density values less than zero, which was

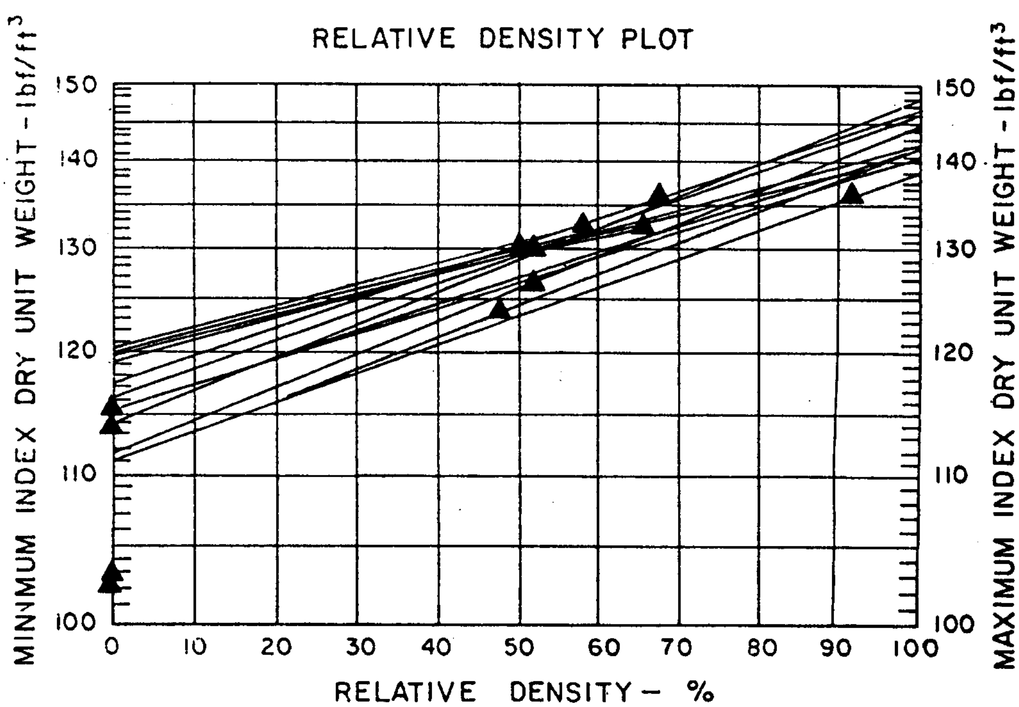

Figure 1.—Results of in-place density measurements at Jackson Lake Dam (1 lb/ft^3 = 16.01 kg/m^3).

likely due to combining layers. Figure 2 shows the results of SPT testing in the embankment. The data are plotted on the Gibbs and Holtz relative density chart. Only sands applicable to the chart are plotted. Correlation of in-place relative density, with penetration resistance inferred relative density was in general agreement but there was some data scatter. Based on these measurements, the Jackson embankment was removed and replaced for seismic modification.

Bully Creek Dam

At Bully Creek Dam, there were exposures of gravelly alluvium and fine wind blown deposits that were accessible by shallow test pits, at the down stream toe of the dam. No de-watering was

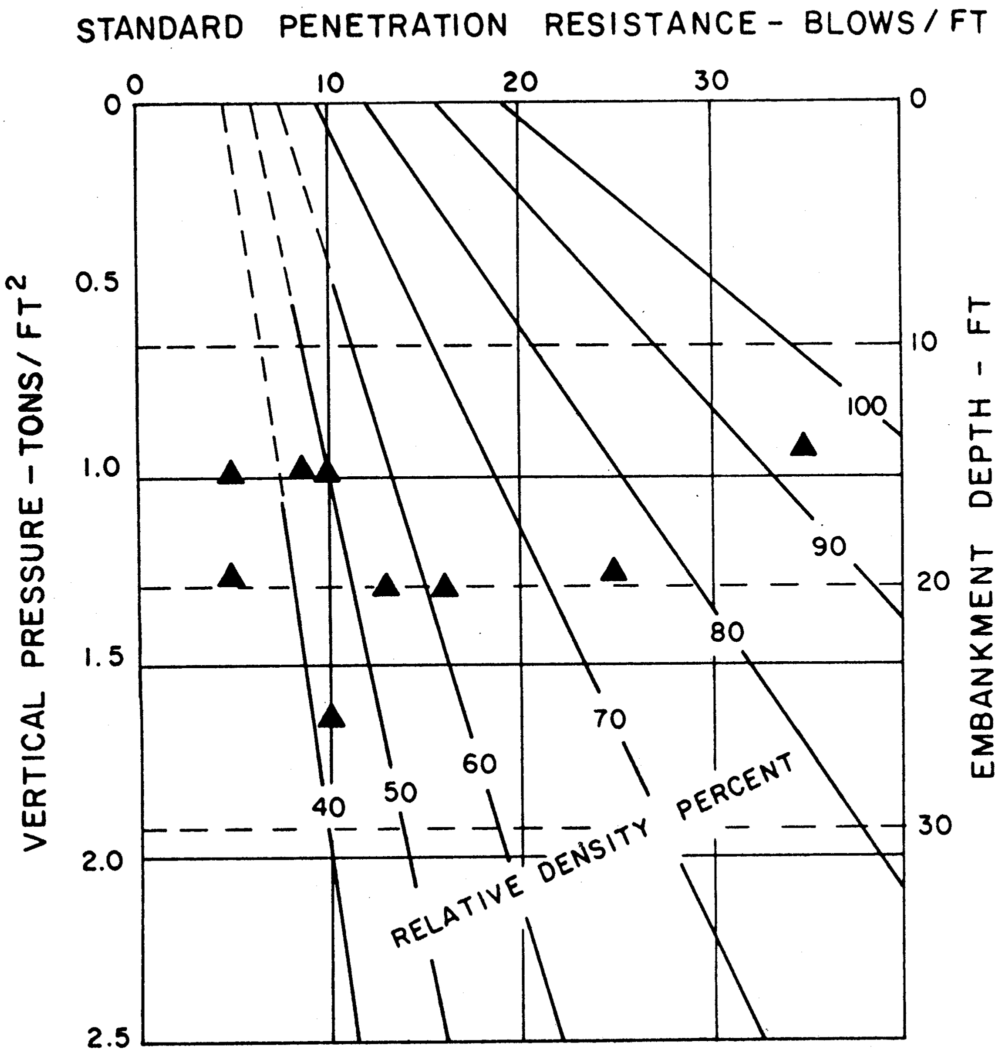

Figure 2.—Results of penetration resistance measurements in clean sands at Jackson Lake Dam (1 tsf ≈ 1 kg/cm²).

required. 50 cm (20 in) diameter sand cone tests were performed in the gravels, and 20 cm (8 in) sand cones and block samples were taken of the windblown materials (*12*). Results of the relative density tests are summarized in Figure 3. Four of the alluvium samples had relative densities of 20 to 40%. One test resulted in negative relative density, which was probably caused by layer mixing. Two of the windblown fine sands, with lower minimum and maximum densities, had very low relative densities. The conditions measured at the downstream toe do not necessarily reflect conditions under the shells of the dam. Testing is underway on the block samples of windblown material to simulate wetted conditions under the shells of the structure. In-place density data indicate the wind blown material may be subject to collapse upon wetting.

Bradbury Dam

Bradbury Dam presented a unique opportunity to compare penetration resistance data to in-place relative density. The decision to remove the alluvium was based on SPT, and BPT along with confirmatory low cross hole shear wave velocity data. There were a few in-place density tests performed at depths of 2-3 m (8 to 10 ft) in early investigations at the downstream toe of the dam. These tests were performed with 1.8 m (6 ft) diameter water replacement ring methods (ASTM D 5030) (*1*). The materials were classified as poorly-graded and well-graded gravels (GP,GW). Using the in-place density data of the control fraction from Castro (*13*) and the vibrated maximum density from Wahler (*14*), calculated relative densities for the nine tests are 91, 83, 50, 45, 20, 16, 16, 2, and -29%.

The most economical method of improvement was to excavation and replace the downstream alluvium and add a berm. This allowed for deeper in-place density data and direct comparison to the SPT and BPT borings. A plan was devised to measure in-place densities near the boring locations. A total of 14 in-place density tests were taken at 10 locations. The multiple tests at a single location indicate layering was present, and several tests may have been taken in each layer. Details of this testing were documented in an internal memorandum (*15*).

The tests were performed with a 50 cm (20 inch) sand cone. A problem with such large cones is that the template rides on top of the gravel particles. Roughness corrections were not measured during the tests, but a later examination of roughness error indicated this was not a significant. If roughness errors occurred, they would only increase relative densities by only about 10%.

Table 1 summarizes the physical properties of the results of the testing. The soils are classified as poorly- to well-graded gravels and sands. Several silty sands and a silt layer were tested. For those soils, the degree of compaction from the standard proctor test was evaluated, and several soils had a low degree of compaction, of less than 90%. For the soils where relative density tests were performed, most particles were smaller than 75 mm (3 in) control fraction size. Only one sample, number 10A, had 23% oversize.

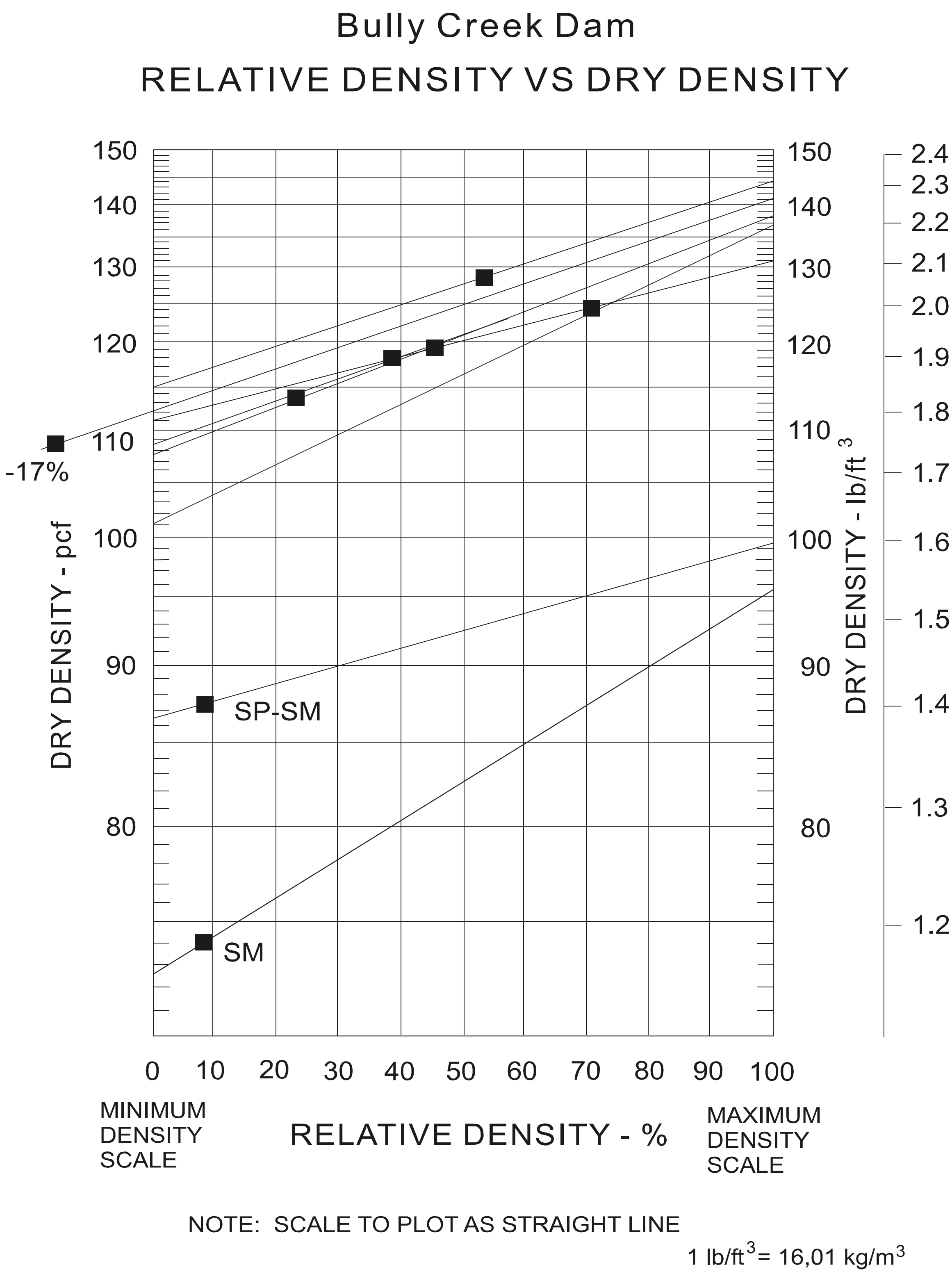

Figure 3.—Results of in-place density testing at Bully Creek Dam (1 pcf = 16.01 kg/m^3).

Table 1.—Summary of physical properties test results, Bradbury Dam modification

Test location	Soil classification	Gravel (%)	Sand (%)	Fines (%)	Maximum size
1A	SM	0	64	39	#8
1B	(SP)g	29	70	1	-75 mm
1C	SM	0	84	18	#8
2	SM	4	82	14	-9.5 mm
3	(SW)g	46	52	2	-75 mm
4	(GW)s	64	34	2	-75 mm
5	(GP)s	54	42	4	-75 mm
7	s(ML)	0	36	73	#8
8A	SP		98	2	#8
8B	s(CL)	0	38	72	#8
9	(GW)s	74	23	3	-75 mm
10A	(GS)sc	76	22	2	150 mm 23% OS
10B	(SP)g	26	71	3	19 mm
10C	(GW)sc	61	36	3	75 mm - 5% OS

The tests were located near the old pre-existing drill holes, and survey control was used to locate the tests. There was a coarse overburden layer overlying some finer gravels and sands. Testing of this coarse layer would have required larger ring water replacement testing. This upper coarse material was the same layer tested by Whaler. The lower layers were targeted for testing due to finer size and control fraction considerations.

Figure 4 summarizes the results of the in-place density testing. Relative densities ranging from 19 to 44% in four out of five tests (test numbers 4, 5, 9, 10A, and 10C) were measured in gravelly soils . These uniform gravels were very loose and could be easily excavated by hand. A fifth test in gravel at location 4 had a higher relative density of 75%. The sandier soils had higher relative densities. Two Silty Sands (SM), Tests 1C and 2, had relative densities of 73 and 85%. Gravelly sands had relative densities ranging from 33 to 74%. An overall view of Figure 4 shows that most of the alluvium had relative densities of less than 60%.

Penetration resistance data from SPT and BPT borings were carefully examined to find the penetration resistance near the testing interval. Table 2 and figure 5 show the results of the SPT and BPT predicted relative density according to the Gibbs and Holtz chart. In some cases, a range of penetration resistance is shown on Table 2 due to uncertainties in locations and layer transitions.

At test locations, 3, 4, and 5, the BPT data predicted the measured relative density accurately in gravels and sands with less than 75 mm (3 in) maximum size particles. Corresponding SPT data had higher relative densities due to particle interference. SPT data were corrected for sand values by using the penetration-per-blow technique. In this correction, the penetration rate in a thin sand layer is extrapolated. These corrections resulted in lower relative densities. At test location 8A in a poorly-graded sand, the SPT predicted the measured relative density accurately. At locations, 1 and 10, the BPT predicted relative density is greater than the measured relative density. At test location 10, the high predicted relative density could be due to interference from

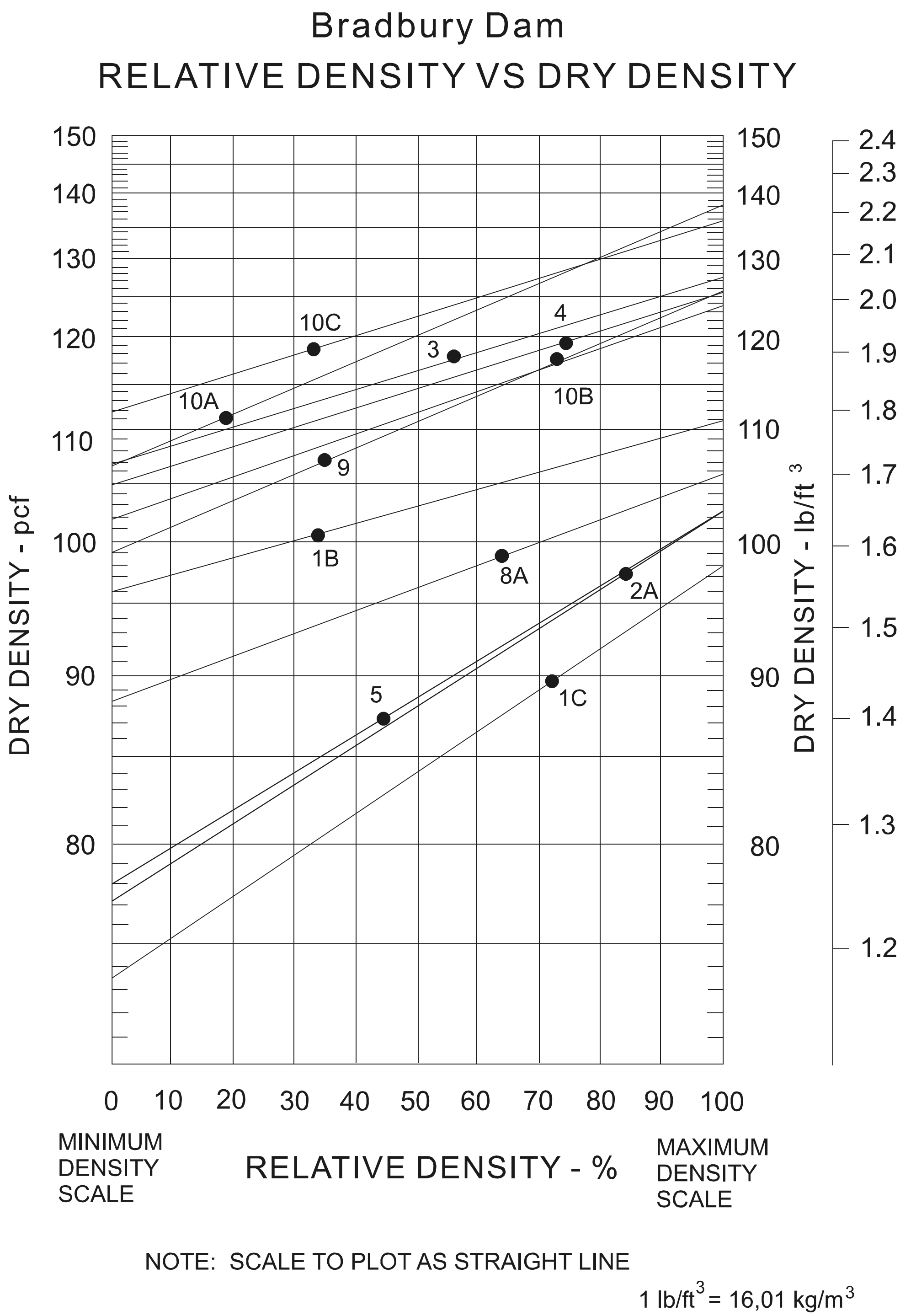

Figure 4.—Summary of in-place density data from Bradbury Dam (1 lb/ft^3 = 16.01 kg/m^3).

Table 2.—Summary of relative density comparisons, Bradbury Dam modifications

Test location	Relative density (%)	SPT N60 Value	SPT N60 Gravel corrected	Estimated relative density SPT a - %	Becker Penetration N60	Relative density from BPT a %
1A		53		92	15	52
1B	33	113	33	75	15	52
1C	73	16		53	22	64
2	85	14	6	<40	23-31	63-71
3	58	60-58	33-36	67-69	23-25	60-62
4	75	54		89	34-39	73-77
5	44	32-49	36	69-73	14-16	45-50
8A	63	22-23		57-60		
9	35				21-22	57-58
10A	19				29	73
10B	74				31	76
10C	33				35	80

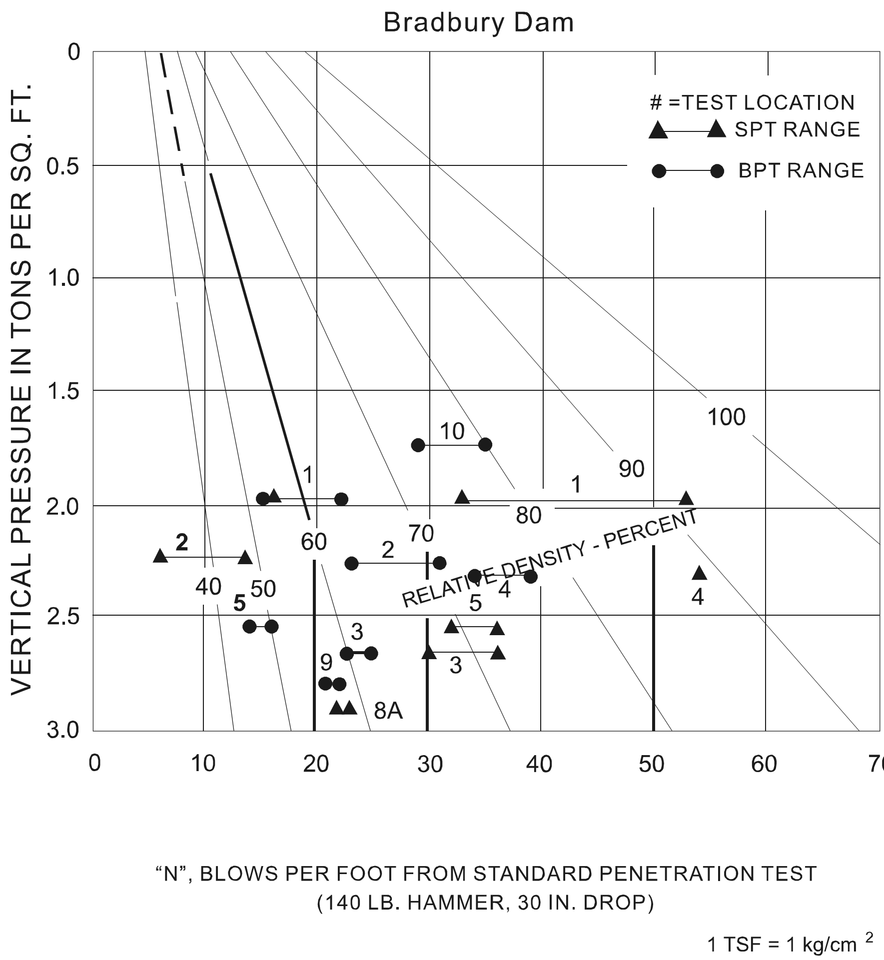

Figure 5.—Summary of predicted relative density from penetration resistance tests (1 tsf ≈ 1 kg/cm³).

300 mm (6 in) maximum size particles. Penetration data for silty sands are not applicable to the Gibb and Holtz chart, and if applied, will result in low estimated relative densities.

Data from these tests are very limited, and there is considerable uncertainty and scatter among the data. But the data do indicate that the BPT may be a reliable test in minus 75 mm (3 in) gravels. There is some evidence that, with 150 mm (6 in) particles, interference occurs and the relative density is overestimated. If more data had been collected, we may have been able to look at the information statistically and draw conclusions with greater confidence. Engineers are encouraged to collect these data in the future if the opportunity exists. In-place density measurements are expensive, but given the uncertainty with the BPT, collection of these data, will help improve confidence of predictions and the investment should be made.

Conclusions

From the above information it has been shown that reliable in-place density measurements can be made on natural soils, providing proper test procedures are used and precautions are taken to avoid errors inherent in measuring in-place density of natural alluvium, such as:

- Being sure the test hole size is representative of the soil being tested, and that the laboratory test on the control fraction can be correlated to the total material.

- In coarse soils, using roughness calibrations for test hole excavations. Roughness errors can result in lower in-place density.

- Mixing of layers of alluvium - resulting in erroneous values of relative density.

- Hole squeezing of wet soils resulting in high values of relative density.

- Disturbance or compaction of soils with construction equipment resulting in densification.

- Contraction in volume of soils when they are de-watered due to increased capillary stresses resulting in densification of the soil.

Results of in-place density testing of alluvium show considerable scatter. This scatter is to be expected in alluvium. Negative values of relative density usually result if the layers of uniform soils are mixed together. The trends of the data indicate that alluvial soils have relative densities which range from 20 to 70%. The data indicate that some uniform gravel alluvium can have lower relative densities than the sand. These low relative density values indicate the materials are liquefiable in earthquakes.

The data were taken at the toes of the dams and do not represent consolidated conditions under the shells of the embankments.

When attempting to correlate in-place relative density to penetration resistance, there is considerable scatter in the data. However, when the data are carefully examined, some trends occur. Limited data were developed in these studies. The Becker test appears to predict relative density correctly for minus 75 mm (3 in) gravelly soils. There is some indication that in soils with maximum size of greater than 150 mm (6 in), the predicted relative density would be high due to particle interference. SPT in gravelly soils results in unreliably high predictions of relative density.

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