Stress Wave Methods in Civil Engineering

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ABSTRACT

The 20th century saw rise to an array of analysis and testing methods developed using stress wave propagation theory. Stress wave techniques are now used in highway projects for site exploration, quality control and forensics of foundations, construction control and normalizing data from standard penetration and Becker penetration tests. This paper summarizes two projects in detail, one the calibration of SPT drill rigs used on NCDOT projects and one recounting energy and shaft resistance measurements on Becker Penetration testing for an earthfill dam in California. Significant variation of individual rig energies were measured around the typically accepted average values for both manual and automatic hammers in the SPT calibration, and the use of Becker Penetration testing for determining liquefaction potential of *in situ* soils was reviewed.

INTRODUCTION

The 20th century saw rise to an array of analysis and testing methods developed using stress wave propagation theory. Growing from the theory of elasticity for materials loaded by a short displacement or force pulse, these methods were applied to petroleum exploration, material property determination and a large subset of civil engineering problems. Some common applications of stress wave techniques in civil engineering practice are briefly reviewed.

APPLICATIONS IN HIGHWAY PROJECTS

Exploration and Seismic Characterization

Many geophysical exploration methods make use of stress wave propagation through the soil. Compression, shear or Rayleigh waves are generated either on the surface or inside a hole bored into the soil. One or more receivers (typically geophones) are placed on the ground surface or in additional bored holes to measure the time required for the waves to travel from the source to the receiver. Based on the magnitude, speed and type of wave detected by the receiver, changes in wave velocity, and thus changes in soil strata or underground features can be measured and identified. Reflection and refraction surveys, downhole surveys, crosshole surveys and spectral analysis of surface wave methods all make use of these concepts.

For example, seismic cone penetration testing (CPT) uses the concept of downhole seismic surveys. In this test, the CPT cone is instrumented with an accelerometer to act as a receiver. At specified depths, a plate on the surface is struck laterally with an instrumented hammer or other mechanical input to generate shear waves in the soil. The time between impact and the received signal can then be interpreted to shear wave velocity using the known depth of penetration.

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The resulting shear wave velocity profiles from this class of testing methods is then used to characterize the low strain stiffness of the soils on the site. This has become particularly necessary in classifying project sites for seismic events, where soils with low shear moduli tend to amplify incoming ground motions due to near or distant earthquakes. The International Building Code uses shear wave velocity and conservative correlations of cone and standard penetration test data to shear wave velocity to determine the level of base acceleration a structure must withstand.

Quality Control, Quality Assurance and Forensics

Stress wave methods are also commonly used to determine the integrity and length of known or unknown foundations, assure the quality of driven piles and drilled shafts and determine the extent of damage or condition of structural members. High strain dynamic load testing considers one dimensional travel of compression waves, and is commonly used to assess the static capacity of piles or drilled shafts during or after the foundation element's installation. High strain testing also monitors the stresses in the pile, the energy transferred by the hammer and the integrity of driven piles during installation.

The propagation of compression waves also forms the basis for low strain integrity, or impact-echo testing. In this case, a stress wave is generated by impacting the pile top with a hammer and observing pile top or pile side velocity data for reflected compression stress waves for evidence of the pile toe or major changes in cross sectional area. Impact echo tests are also extensively used in above ground structural applications to look for voids or other defects.

Parallel seismic testing uses a similar technique, except the received signal is taken in the soil adjacent to the pile. The change from pile material to soil is exploited to determine the end of the pile by detecting a change in wave speed. Bending wave tests are similarly designed, although more types stress waves are considered.

For drilled shafts, cross hole sonic logging is used to verify continuity of concrete between a system of access tubes cast along the shaft's length. Variations in the arrival time of a transmitted signal to a receiver in an adjacent tube indicate a change in the speed of wave transmission. A lost or weakened signal, or significant reductions in wave speed indicate concrete of lower quality or the presence of voids in the shaft.

Construction Control

The propagation of stress waves through rock and soils due to construction activities can also be problematic for neighboring or existing structures. When blasting or pile driving occurs, the stress waves generated can damage building components, or at least surprise the occupants enough to look for damage. In this case, the generated stress waves are more a nuisance than a useful tool, so steps must be taken before and during construction to mitigate the generation or catalog the status of near-by structures.

Normalizing Data of Penetration Tests

Force and velocity measurements taken on standard penetration test (SPT) or Becker Penetration Test (BPT) drill strings are analyzed for the energy transferred from the hammer to the drill string. Because different hammer and driving system conditions can result in widely varying blow counts in the same soil conditions, previous researchers have noted that the recorded blow count should be corrected. The result is a calibrated blow count at a standard energy for both the SPT and BPT test. These measurements will be discussed in more detail for the remainder of the paper.

SPT ENERGY MEASUREMENTS

The SPT is the most commonly used exploration method for characterizing soils. In this test, a 140 lb hammer is dropped 30 inches to advance a split spoon sampler on the end of the drill string. The sampler is advanced 18 to 24 inches, with the number of blows recorded in six inch intervals. The SPT N-value is the sum of the number of blows over the second and third six inch intervals.

Schmertmann and Palacios (1979) recognized that energy transferred by the SPT hammer to the drill rod had a pronounced effect on the measured N-value. It was also noted that the drop system used to allow the hammer to freefall also had a significant effect on the transferred energy. Transferred energy measurements on driven piles and SPT rods are made by instrumenting the driven rod with strain transducers and accelerometers, such that the force and velocity generated in the rod by the impact can be measured with time. The transferred energy is calculated by integrating the product of force and velocity over time. The reported transferred energy is the maximum value of this integration. A typical set of force, velocity and energy curves are shown in Figure 1.

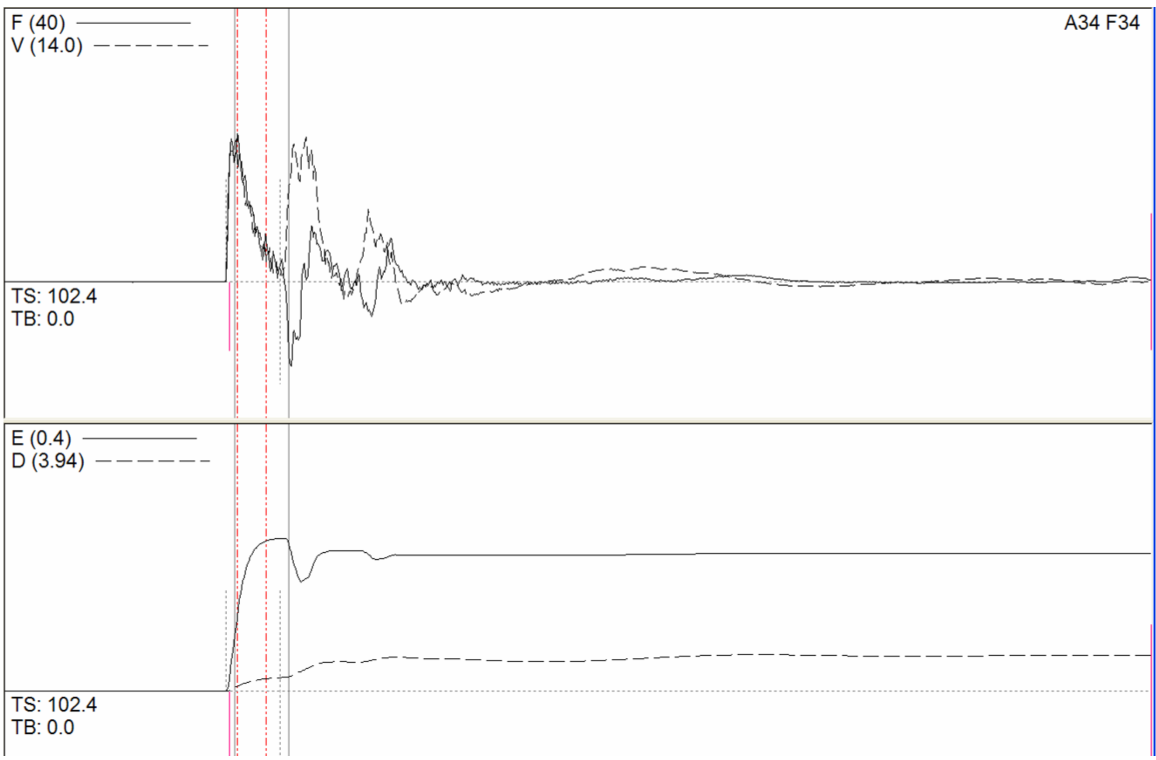

Figure 1. Force (F), Velocity (V), Energy (E) and Displacement (D) curves from an SPT calibration.

The baseline energy transfer ratio has been set to the average transferred energy for manual SPT hammers, or 60%, which yields the corrected blow count N_{60}, as shown in (1) (Skempton, 1986). This level was chosen because most of the traditionally used correlations were developed using manual hammers.

$$N_{60} = C_r C_s C_d \frac{ETR_{hammer}}{60\%} N \tag{1}$$

In (1), the factors C_r, C_s, and C_d are corrections to the measured N-values for rod length, sampler length and borehole diameter, respectively. ETR_{hammer} is the average transferred energy based on general hammer type or measured transferred energy from stress wave measurements. The hammer correction, ETR/60%, is recommended to be 60% for manual safety hammers and 80% from automatic trip hammers in the absence of measurements. While the sampler and borehole diameter corrections are generally one for most tests, the rod length correction factor increases from 0.75 to 1 in a step wise fashion as the rod length increases from 4 m to 10 m. This correction generally accounts for lower transferred energies measured at lower depths of penetration where the soil strata are soft and tensile reflections from the pile toe reduce the nominal energy transferred from the hammer to the rod.

NCDOT Drill Rig Energy Calibrations.

In late 2005, energy measurements on drill rigs with SPT hammers owned by NCDOT and NCDOT consultants were performed. Twenty-eight rigs were each calibrated over a range of penetration depths of 8.5 to 60 feet. Of the rigs tested, seven were manual drop hammers while the remaining 21 had automatic drop mechanisms. For each 18 inch SPT sample collected, the transferred energy was averaged. At the end of testing, all energy measurements on a rig were averaged. The overall average results, as well as the range of energies measured on each rig, are shown in Figure 2.

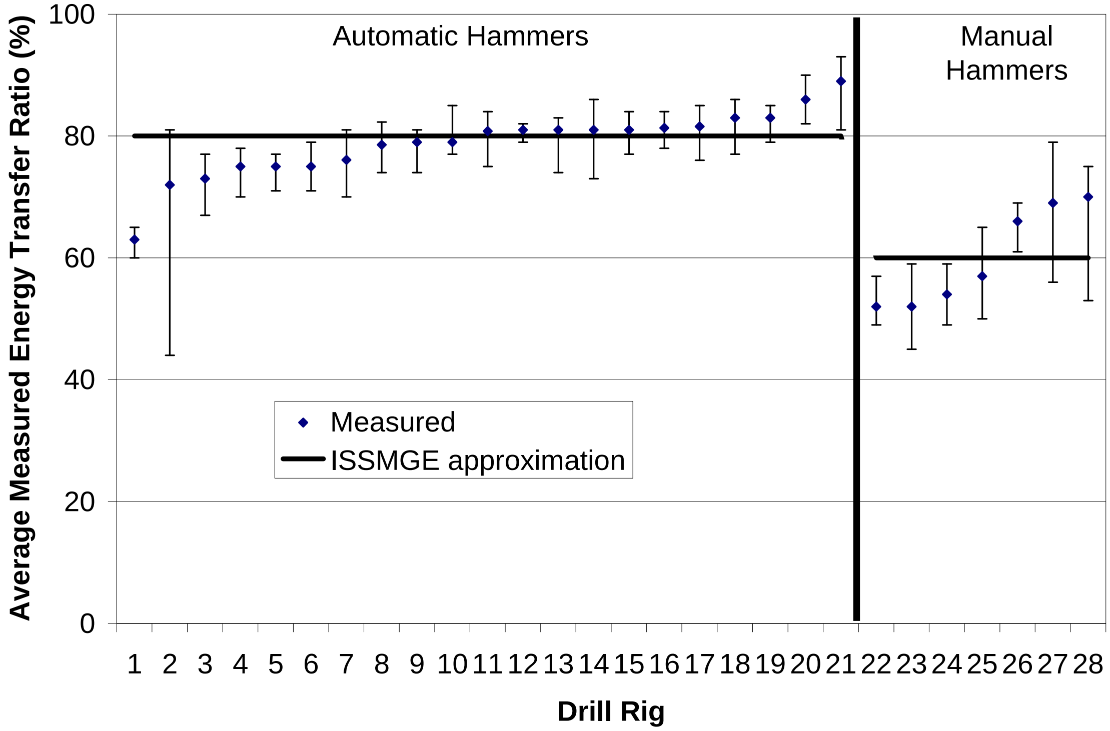

Figure 2. NCDOT SPT Hammer Calibration Results

The measurements made on the rigs used on NCDOT projects shows an overall average energy transfer ratio of 79% and 60% for automatic and manual drop rigs, respectively. These overall averages are very similar to the observations reported by Skempton (1986). The importance of calibrating individual rigs is shown as some hammers are consistently below or consistently above the values recommended for each hammer type in the aggregate. With the exception of drill rig 2, the automatic hammers have less variability over the length of the boring than the manual hammers, a not unexpected result.

In general, the lower bound measurements for each drill rig shown in Figure 2 occurred when the SPT sampler was at a penetration of less than 10 m. This lends some additional support to the use of the rod length correction factor discussed previously. This trend is currently under investigation by N.C. State and NCDOT personnel (Valiquette, 2008).

BECKER PENETRATION TESTING

In the late 1950's, the Becker Penetration Test (BPT) was developed in Canada as a penetration type test to provide index properties similar to the SPT N-Value, but in soils with significant gravel content. The BPT is performed using a 6-5/8 inch drill rod, that consists of a double-walled system arranged such that the driving forces are carried by the outer pipe, while the inner pipe floats independently. The Becker drill string is often advanced with a closed end.

To advance the larger diameter rod, the BPT has traditionally used a double acting diesel hammer. Similar to SPT, the data from a BPT is logged as the number of blows required to advance the rod one foot, which yields the BPT blow count, N_b. Similar to the SPT, N_b is corrected to a constant transferred energy, as measured by either direct stress wave measurements as discussed previously or by monitoring the hammer's bounce chamber pressure.

In the last two decades, the BPT has been used, via correlation to SPT N_{60}, as a way to estimate the liquefaction potential of gravel deposits. This method has been used by the Bureau of Reclamation to account for the seismic risk of earthfill dams. Harder and Seed (1986) initially developed a correlation between N_b and N_{60}; Sy and Campanella (1993) extended the number of data points in the correlation, while simultaneously investigating the effects of the resistance developed along the side of the casing on the value of $N_{b.}$

Sy and Campanella (1993) suggested the following steps for correcting the BPT data and correlating it to N_{60} from an SPT:

1. Monitor BPT test during driving to determine energy transfer
2. Correct the recorded blow count to N_{B30}.
3. Select stress wave data from blows obtained at critical depths to determine shaft resistance with CAPWAP (PDI, 2006) or using static methods.
4. Using N_{B30} and the measured shaft resistance, determine equivalent SPT N_{60}.

Once N_{60} has been determined, existing methods for evaluating the liquefaction potential through correlation to cyclic stress ratio (for example, Youd and Idriss, 2001) can be used.

Case History: Earth Dam, California

On a historic earthfill dam in California, Becker testing was performed to evaluate two distinct soil strata. One strata was located between 10 and 20 feet, while the other was located between 70 and 85 feet. A. Link Belt 180 closed end diesel hammer with a ram weight of 1.73 kips and a rated energy of 8.1 kip-feet was used to advance the drill rod. Hammer energy was measured by instrumenting the rod with strain transducers and accelerometers. The shaft resistance at each depth was measured by performing both static uplift tests and by evaluating the stress wave data using CAPWAP. CAPWAP is a software program for analyzing stress wave data on piles, which uses inverse solution methods to back calculate the soil resistance and damping profile based on an input force curve and resulting velocity curves.

Table 1 summarizes the measured blow count, transferred energy, corrected BPT blow count, and shaft resistance calculated from uplift testing and by CAPWAP. The correlated SPT N_{60}. is determined by combining the shaft resistance and corrected BPT blow count and reading the estimated SPT N_{60} as shown in Figure 3 For many penetration depths, the resulting correlated N_{60} is undefined for the data available, but extrapolation of the existing trend lines in the figure would lead to N_{60} values greater than 80 blows per foot.

The uplift test and CAPWAP results can be also compared, as shown in Figure 4.The general trend of this correlation is very similar to those reported for driven piles in compression (Likins et al., 1996). At blow counts less than approximately 15 blows per foot, CAPWAP occasionally overpredicts compared to static tests, while at blow counts approaching refusal, the capacity is not fully mobilized due to the very small displacements of the pile under each hammer blow.

Table 1. Summary of Becker Penetration blow counts, energy transfer and shaft resistance at selected depths.

Becker Test	Approx. Pen.	Blow Count	Energy Transfer	NB30	CAPWAP Shaft	Static Uplift Penetration	Static Uplift Shaft	Correlated SPT N60
	ft	bl/ft	%	bl/ft	kips	ft	kips	bl/ft
BPT-07-01	73	94	31	97	29	70	24	>80
BPT-07-01	90	89	28	83	64	85	65	38
BPT-07-02	70	64	36	77	32	70	34	>80
BPT-07-02	84	80	35	93	37	80	36	>80
BPT-07-03	71	68	25	57	35	75	41	59
BPT-07-03	83	203	35	237	52	85	62	>80
BPT-07-04	75	34	37	42	12	75	17	74
BPT-07-04	85	109	38	138	18	85	13	>80
BPT-07-04A	70	56	34	63	24	NP	NP	>80
BPT-07-04A	78	84	34	95	32	75	27	>80
BPT-07-05	68	132	27	119	97	NP	NP	16
BPT-07-05	76	600	27	540	134	76	183	???
BPT-07-06	15	67	34	76	30	15	33	>80
BPT-07-06	22	59	32	63	31	25	37	>80
BPT-07-06	30	33	25	28	28	NP	NP	22
BPT-07-07	18	36	29	35	24	10	8	40
BPT-07-07	25	31	32	33	31	30	139	27
BPT-07-08	13	34	28	32	15	10	12	50
BPT-07-08	20	203	30	203	12	20	9	>80
BPT-07-08	28	208	35	243	29	NP	NP	>80
BPT-07-09	15	70	34	79	21	10	9	>80
BPT-07-09	21	85	31	88	23	NP	NP	>80
BPT-07-10	12	28	35	33	7	9.5	3	64
BPT-07-10	21	97	27	87	16	NP	NP	>80
BPT-07-11	14	53	29	51	11	10	9	>80
BPT-07-11	20	93	27	84	30	20	41	>80
BPT-07-12	15	21	33	23	9	10	7	41
BPT-07-12	20	429	38	543	27	20	32	>80
BPT-07-13	13	36	24	29	9	10	5	54
BPT-07-13	20	127	29	123	31	20	42	>80
BPT-07-14	12	17	27	15	6	10	3	28
BPT-07-14	15	151	37	186	11	NP	NP	>80
BPT-07-15	12	38	28	35	6	10	3	68
BPT-07-15	15	170	30	170	13	NP	NP	>80

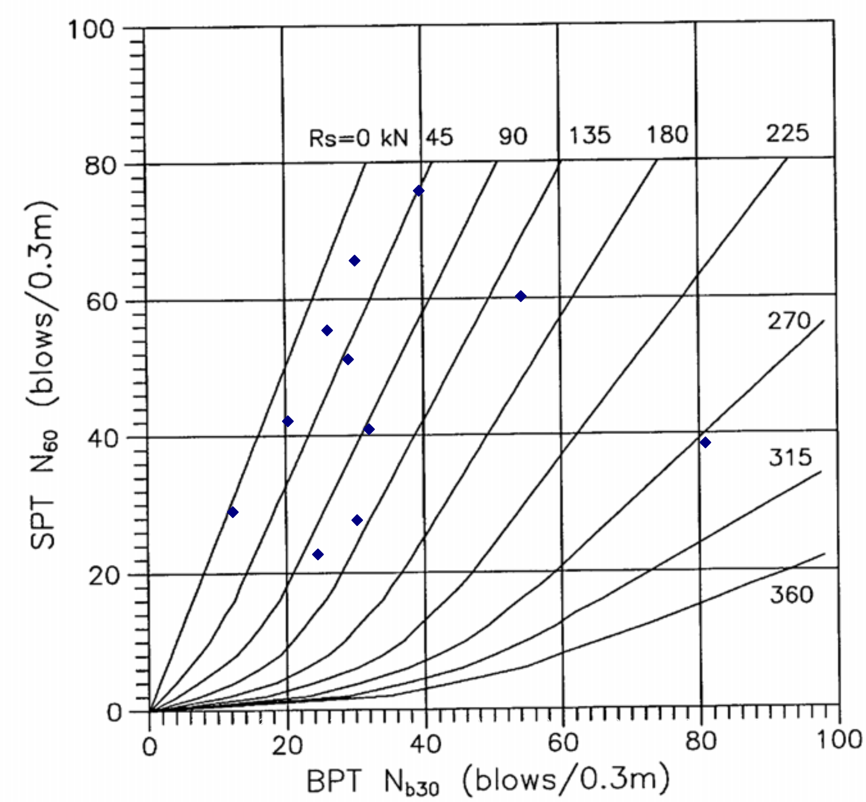

Figure 3. Correlation of BPT to SPT results considering side friction (Sy and Campanella, 1993).

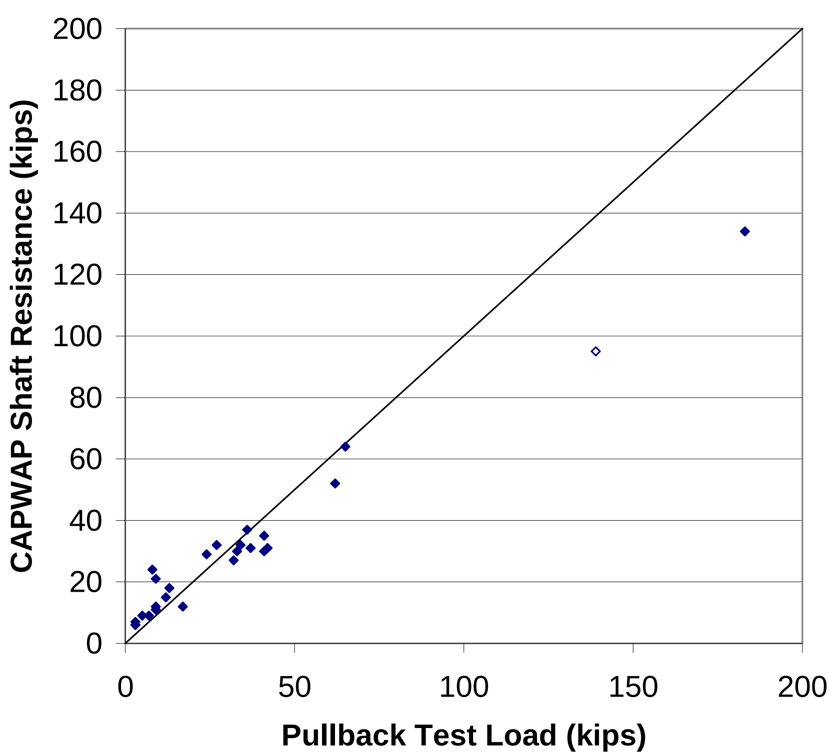

Figure 4. Comparison of CAPWAP and Pullback Test Loads at similar depths.

To estimate liquefaction potential, the correlated SPT N_{60} results can be further correlated to the cyclic resistance ratio (CRR) from the chart developed by Seed et al. (1985) and updated by Youd and Idriss (2001). This figure is reproduced as Figure 5. As shown in Table 1, only four Becker Penetration test locations have correlated N_{60} values of less than 30, where CRR is defined in Figure 5.

For example, BPT 07-06 at 30 feet of penetration yielded a correlated $_{N60}$ of 22 blows per foot. A more detailed look at the soils each location would tend to lead to CRR values from Figure 5 of 0.24 in clean sands and 0.53 in sands with significant fine contents. To compute a factor of safety against liquefaction in this material, the cyclic stress ratio is computed based on the total and effective vertical stresses and the expected magnitude of acceleration of the ground due to the design earthquake loading (Youd and Idriss, 2001).

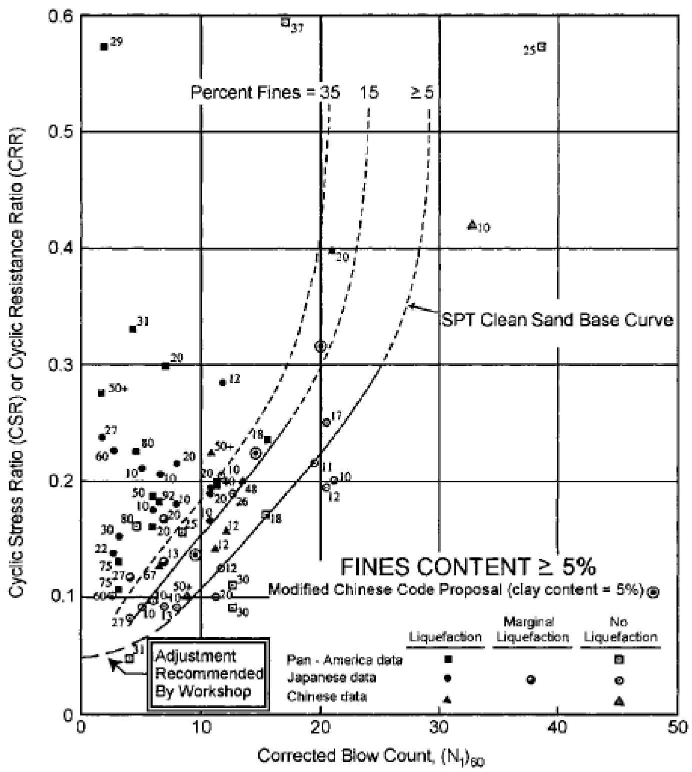

Figure 5. SPT vs. Cyclic Resistance Ratio from Youd and Idriss, 2001 (Modified from Seed et al., 1985).

CONCLUSIONS

Stress wave methods have had a pronounced effect on exploration, quality control, forensic and construction efforts in a wide range of engineering applications. This paper has reviewed two specific data sets. In the first, compression wave measurements on drill strings were used to calibrate SPT drill rigs to provide N_{60}. In the second, Becker penetration testing was performed with stress wave energy measurements and shaft resistance measurements to correlate the BPT blow count to the SPT N_{60}, with the ultimate goal of determining whether specific locations in the earthfill dam were susceptible to liquefaction.

Because SPT testing is still so widely used and is heavily based on the correlations made by others, the normalization and standardization of the blow count to a set 60% energy transfer is very important.

While, on average of a large set of manual and automatic hammers the energy transferred will approach 60 or 80%, respectively, individual hammers may be significantly higher or lower.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the Mr. Don Moore and the North Carolina Department of Transportation Geotechnical Engineering Unit for organizing and overseeing the calibration of SPT rigs. Ms. Anna Klesney collected the Becker Penetration Testing data; her efforts are greatly appreciated. Finally, the U.S. Department of Transportation's Eisenhower Transportation Fellowship program sponsors the first author.

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