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# Bearing Capacity Factor Nq Estimation of Pilani Soil Using Ultrasonics

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## Abstract
*As per IS: 6403-1981, bearing capacity factors Nc, Nq and N□ are required in order to get the net ultimate bearing capacity. They depend strictly on the soil's angle of shearing resistance. Soil's cohesion is also required in order to calculate net ultimate bearing capacity. Cohesion and angle of shearing resistance of soil is determined using drained direct shear testing, unconfined compression testing (undrained) or undrained triaxial testing depending on soil condition at site, all of which require complicated experimental setup. Lengthy calculations are also involved. As an alternative to it, ultrasonics has been used in the present study to obtain estimated value of Nq for Pilani region soil. Knowing ultrasonic P wave velocity, estimated value of cohesion, angle of shearing resistance and Nq can be obtained from the calibration curve developed in the present study. Other bearing capacity factors are then obtained using equations available in the literature. Consequently, net ultimate bearing capacity can also be conveniently determined. Ultrasonic P wave velocity determination through soil requires very simple experimental setup. Developed calibration curve thus has lot of advantages. Similar calibration curves can be developed for other regions soils also simplifying the process of bearing capacity factors and net ultimate bearing capacity determination.*

***Keywords:*** Angle of shearing resistance; Calibration curve; Cohesion; $N_q$; P wave velocity

## 1. Introduction
Structural foundations can be broadly grouped into two categories, namely, shallow foundations and deep foundations. Shallow foundation transmits structural loads to the soil strata at a relatively small depth. As per Terzaghi, shallow foundation is the one which is laid at a depth not exceeding the width of the foundation[1]. Shallow foundations are constructed in open excavations and disturbance of underlying soil is minimal. For reasons of economy, shallow foundations are the first choice of foundation engineer for a structure. Present study concerns shallow foundations (Hanna & Meyerhof, 1981). For shallow foundation constructed with its base at certain depth below ground surface, total pressure at base of foundation is due to weight of superstructure, self weight of foundation and weight of soil fill over foundation[2]. This total pressure is called gross pressure or gross loading intensity. However, soil deformation below base of footing is caused only by the pressure which exists over and above before construction of foundation and superstructure[3]. The difference between gross pressure and overburden pressure at the base of foundation is called net pressure or net loading intensity[4]. If the load at base of foundation is gradually increased, a stage will be reached when load will cause shear failure in surrounding soil. Maximum gross intensity of loading that soil can support before it fails in shear is called the ultimate bearing capacity[5]. Ultimate bearing capacity not only depends on underlying soil properties but also to the characteristics of foundation (size, shape and depth) and mode of loading, vertical, inclined, axial, eccentric etc. Net ultimate bearing capacity is maximum net intensity of loading at the base of foundation that the soil can support before failing in shear (Highter & Anders, 1985). Net safe bearing capacity is maximum net intensity of loading that soil can safely support without the risk of shear failure. It is obtained by dividing net ultimate bearing capacity with adequate factor of safety (Ranjan & Rao, 2024). For static loading, taken factor of safety is 2.5 or 3[6]. In Pilani region, it is taken 3. As per IS code recommendations for breaking capacity (IS: 6403-1981), net ultimate bearing capacity $q_d$ based on general shear failure and net ultimate bearing capacity $q'_d$ based on local shear failure (both in

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kg/cm$^2$) should be calculated using following equations:

$$q_d = cN_c s_c d_c i_c + q(N_q - 1)s_q d_q i_q + 0.5\gamma B N_\gamma s_\gamma d_\gamma i_\gamma W'$$

(for general shear failure) [1]

$$q'_d = 0.67cN'_c s_c d_c i_c + q(N'_q - 1)s_q d_q i_q + 0.5\gamma B N'_\gamma s_\gamma d_\gamma i_\gamma$$

(for local shear failure) [2]

In above equations, c is soil cohesion in kg/cm$^2$, q is effective surcharge at base level of shallow foundation in kg/cm$^2$, γ is bulk unit weight of foundation soil in kg/cm$^3$, B is width of foundation in cm and W' is correction factor for water table location (Hjiaj et al, 2005)[7]. Also, $s_c$, $s_q$, $s_\gamma$ are shape factors, $d_c$, $d_q$, $d_\gamma$ are depth factors and $i_c$, $i_q$, $i_\gamma$ are inclination factors. Details about shape, depth and inclination factors is available in IS: 6403-1981. If the water table is likely to permanently remain at or below a depth of ($D_f$+*B*) beneath the ground level surrounding the footing then W'=1[8]. $D_f$ is depth of foundation in cm. If the water table is located at a depth $D_f$ or likely to rise to the base of the footing or above then the value of W' shall be taken as 0.5. If the water table is likely to permanently got located at depth $D_f$<$D_w$<( $D_f$+B ), then the value of W' shall be obtained from linear interpolation. $D_w$ is depth to water table in cm. $N_c$, $N_q$ and $N_\gamma$ are bearing capacity factors. They depend strictly on the soil's angle of shearing resistance ϕ, which is usually expressed in degrees (Kumbhojkar, 1993)[9]. $N_q$ in present study has been obtained from Table 1 of IS: 6403-1981. Linear interpolation has been used for intermediate values of angle of shearing resistance. In order to determine bearing capacity factor, $N'_q$, ϕ' is determined using ϕ' = $\tan^{-1}(0.67\tan\phi)$. For this obtained value of ϕ', $N_q$ is obtained from Table 1 of IS: 6403-1981 using previously explained technique[10]. This gives required value of $N'_q$. As per IS: 6403-1981, bearing capacity factors $N_c$, $N_\gamma$, $N'_c$ and $N'_\gamma$ are determined as follows:

$$N_c = (N_q - 1)\cot\phi \qquad (3)$$
$$N_\gamma = 2(N_q + 1)\tan\phi \qquad (4)$$
$$N'_c = (N'_q - 1)\cot\phi' \qquad (5)$$
$$N'_\gamma = 2(N'_q + 1)\tan\phi' \qquad (6)$$

For ϕ = 0degrees, $N_c$ and $N'_c$ = 5.14. Table 1 of IS: 6403-1981 lists $N_q$ values for ϕ ranging from 0 to 50degrees. This variation has been shown in Table 1 below (IS: 6403-1981, 1981).

**Table 1 $N_q$ variation with ϕ**

| ϕ (degrees) | $N_q$ |
|---|---|
| 0 | 1 |
| 5 | 1.57 |
| 10 | 2.47 |
| 15 | 3.94 |
| 20 | 6.4 |
| 25 | 10.66 |
| 30 | 18.4 |
| 35 | 33.3 |
| 40 | 64.2 |
| 45 | 134.88 |
| 50 | 319.07 |

Angle of shearing resistance and cohesion of cohesion-less soil is obtained from drained direct shear testing (Meyerhof, 1963). Cohesion-less soils have close to zero cohesion (less than 5kPa). Intermediate soils have more than 5kPa cohesion with 75micron finer less than 50%. Angle of shearing resistance and cohesion of intermediate soil is also obtained from drained direct shear testing. Testing technique is quick, inexpensive and simple as compared to triaxial testing. Ease of sample preparation is another advantage in this regard. Cohesive soils have more than 12kPa cohesion with 75micron finer more than 50% (Kumar et al, 2016). Cohesion and angle of shearing resistance for cohesive soil is to be determined from unconfined compression testing or undrained triaxial testing as per soil condition at site Table 1. Unconfined compression testing is relatively simple with respect to triaxial testing (Vesic, 1973). For cohesion-less soil, general shear failure is assumed for $\phi \geq 36^0$ and

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local shear failure for $\phi \leq 29^0$. For intermediate values of angle of shearing resistance, linear interpolation between general and local shear failure is assumed. Also, as per IS: 6403-1981, for void ratio ≤55, general shear failure, for void ratio ≥75, local shear failure and linear interpolation between general as well as local shear failure for intermediate values of void ratio is taken. For c-ϕ (intermediate and cohesive) soils, if soil failure is at low strain (5% or less), general shear failure is taken. If stress-strain curve has continuously rising pattern even at strains of 10 to 20%, local shear failure is taken. Local soil mix taken in present study was either cohesion-less or intermediate type. While determining net ultimate bearing capacity, bearing capacity factor $N_q$ is thus a key parameter (Dewaikar, 2008). Depending on the soil at site, its determination requires drained direct shear testing, unconfined compression testing or undrained triaxial testing. All of them require complicated experimental set-up. As an simple alternative to it, ultrasonic P wave velocity through local soil has been used in present study to obtain estimated value of $N_q$. Calibration curve has been developed for this purpose to obtain $N_q$ knowing ultrasonic P wave velocity and particle size composition of local soil. Net ultimate bearing capacity of soil is an important soil property. It depends on the characteristics of soil system and properties of surrounding environment. Conventional method of testing involves finding out properties of soil and then determining net ultimate bearing capacity. These conventional methods involve disturbance of soil sample, which in turn puts restriction on to the usefulness of the results. Several non-destructive testing (NDT) techniques, have been developed to test materials of civil engineering importance. In these methods of testing, certain non destructive parameters of the material are determined experimentally. Then a correlation is drawn between those measured non-destructive parameters and engineering properties (Brandt, 1955). Net ultimate bearing capacity is one such very important property. During the testing, sample is not destructed mechanically. This makes testing convenient to perform and reliable information is obtained. It also allows performing in-situ testing without disturbing the sample. Wave based non-destructive tests are a special class of non-destructive testing technique. In these methods information about elastic wave travel through the media helps to understand the characteristics of the media (Desai et al, 1995). When elastic waves travel through soil samples, the characteristics of primary and secondary elastic waves changes with changes in properties of the soil such as elastic moduli, density, moisture content, void ratio, porosity, degree of saturation and particle size composition (Sudhiram, 1985). Hence variation in any one of these parameters can be correlated with the changes in the behaviour of elastic waves provided other parameters remain unaltered. Net ultimate bearing capacity of soil is also dependent on the above mentioned characteristics of soil. Hence a correlation can be developed between wave characteristics and net ultimate bearing capacity of the soil. Ultrasonic pulse velocity testing is a long established wave based non-destructive testing method. It involves determination of velocity of longitudinal waves through the sample (Molyneux & Schmitt, 2000). Velocity measurement is then correlated with properties of sample such as net ultimate bearing capacity of the sample. In the present study use of ultrasonic technique has been made for testing of soils. This method involves determination of longitudinal (compressional) P wave velocity through sample. This can be achieved by measuring time taken by a pulse to travel a measured distance in the sample. Transducers are placed in contact with the sample and low frequency transducers are used for this purpose. Frequency used was 150kHz which is very small as compared to MHz frequencies used for NDT of metallic materials. Measurement can be done using through transmission technique[11]. In this method transmitting and receiving transducers are placed on the opposite faces of the sample. The axes of the transducers are aligned. Ultrasonic testing is a family of non-destructive testing techniques based on the propagation of ultrasonic waves in the object or material tested. In most common ultrasonic testing applications, very short ultrasonic pulse waves with centre frequencies ranging from 0.1-15MHz and occasionally up to 50MHz, are transmitted into materials to detect

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internal flaws or to characterize materials[12]. Three types of waves are generated by an impulse applied to a solid mass. Surface waves having an elliptical particle displacement are the slowest, whereas shear or transverse waves with particle displacement at right angles to the direction of wave travel are faster (Robertson et al, 1995)[13]. Longitudinal waves with particle displacement in the direction of wave travel (sometimes known as compression waves) are the most important since these are the fastest and generally provide more useful information[14]. Electro-acoustical transducers produce waves primarily of this type; other types generally cause little interference because of their lower speed. They are also called ultrasonic P waves (Chandra et al, 1991)[15]. Ultrasonic wave attenuation is the loss of signal intensity as waves travel through a material (soil water mixture for example), caused primarily by absorption (conversion to heat) and scattering (reflection off internal structures). It is heavily influenced by frequency, microstructure (grain size, porosity), and material damping capacity. Higher frequencies generally increase scattering and, consequently, attenuation[16]. The scattering results from the fact that the material is not strictly homogeneous. In a material with very coarse grains of a size comparable to the wavelength, the scatter can be visualized geometrically. At an oblique boundary the wave is split into various reflected and transmitted wave types. This process repeats itself for each wave at the next grain boundary. Thus the original ultrasonic beam is constantly divided into partial waves which along their long and complex paths are gradually converted into heat because of the always present true absorption. In the frequency range used for testing materials the grain size is usually smaller than the wavelength and under these conditions scatter occurs instead of geometric division, as when the light of a headlamp is scattered by the small water droplets in fog. In the case of grain sizes of 1/1000th to 1/100th of the wavelength, scatter is for all practical purposes negligible (Kumar & Prakash, 2000). It increases very rapidly however, approximately as the third power of the grain size, to make itself felt at sizes from l/l0th to the full value of the wavelength, to such an extent that testing may become impossible if the material concerned is anisotropic. The second cause of the attenuation, viz. true absorption, is a direct conversion of sound energy into heat. Absorption can roughly be visualized as a sort of braking effect of the oscillations of the particles, which also makes it clear why a rapid oscillation loses more energy than a slow oscillation, the absorption usually increasing with the frequency, but at a rate much slower than the scattering (Krautkramer & Krautkramer, 1990). In the present study, particle size of local soil used was 300micron passing. Ultrasonic P wave velocity obtained was 340-510.5m/s range. Low ultrasonic frequency (150 kHz) materials tester for civil engineering applications was used.

## 2. Experimental Details

Locally available soil was used as the main experimental material. One of the reason for selecting local soil was to better understand its behaviour in view of major expansion plan being undertaken at BITS Pilani. Buildings are proposed and are under construction for new library complex, additional hostel complex, additional residential accommodation for faculty, new class rooms etc. Experimental work required coarse grained soil as well as fine grained soil. Coarse grained soil was collected from desert stretch located some distance from BITS campus. Soil from this location was predominantly coarse grained. Amount of fine grains in the soil was very small. Soil sample had an in-situ moisture content of 4 to 5%. It was oven dried for 24hours before using it for experimental work. Experimental work also required fine grained soil. This soil was available locally close to the BITS campus at a depth of 12 to 15meters. It was collected in the month of April from a deep ditch excavated at that location. Water table in the area was approximately at a depth of 150meters and the in-situ water content of the soil was 6%. This soil was also oven dried for 24hours[17]. Coarse grained soil passing 300micron sieve and retained on 150micron sieve was taken for experiments. Similarly fine grained soil passing 150micron sieve and retained on 75micron sieve as well as passing 75micron sieve and retained on pan was also used for the experiments. Proportion of these two silty clay was half each on

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weight basis. Five different sand, silty clay mixtures were tested with silty clay content 10%, 30%, 50%, 70% and 90% respectively on weight basis. Coarse grained soil retained on 150micron sieve has been classified as sandy Table 2. Similalrly fine grained soil retained on 75micron sieve as well as on pan have been classified as silty clay. This classification is based on dispersion test. Sieve analysis of both the oven dried soil samples were made. Particle size distribution obtained after doing the sieve analysis of both the samples have been indicated in Table 2 (Kumar, 2002). Water content in all the five soil mixtures was taken as 10%, which is worst in-situ. As soil mixtures were freely draining type, drained direct shear testing was done to find out cohesion and angle of shearing resistance. As per the values obtained, these soil mixtures were classified as cohesion-less or intermediate type. At 10% silty clay content, soil is cohesion-less[17]. Depending upon the value of angle of shearing resistance, general shear failure, local shear failure or linear interpolation between general and local shear failure is applicable. For other silty clay contents, soil is intermediate type. As failure strain is less than 5%, general shear failure is applicable at these silty clay contents. Bearing capacity factor $N_q$ of tested silty contents has been obtained from linear interpolation from Table 1 for the obtained angle of shearing resistance values. Cohesion and angle of shearing resistance values obtained from drained direct shear testing on these soil compositions is shown in Table 3. Table 3 also lists $N_q$ values for these soil compositions. Experiments were also conducted to determine ultrasonic P wave velocity through soil sample at these silty contents and at 10% water content. Through transmission technique was used. Testing was done using piezoelectric transducers at 150kHz frequency on 1.7cm thick samples having 6cm x 6cm plan area and compacted nominally in a wooden frame to get bulk density of soil compact as 1.45gm/cc. Piezoelectric transducer had 3.6cm diameter. Grease was used as coupling agent (Kumar, 2025a). Obtained ultrasonic P wave velocities for these compositions is also shown in Table 3. 150micron passing and 75micron retaining as well as 75micron passing and pan retaining silty clay was half each in each soil mixture[20]. Even if 75micron retaining or pan retaining silty clay was other than half each in each mixture, obtained ultrasonic P wave velocity, cohesion and angle of shearing resistance values were found to be about the same[19].

**Table 2 Particle Size Distribution of Local Sand and Silty Clay**

| Particle Size | 2.36mm | 1.18 mm | 600μm | 300 μm | 150 μm | 75μm |
|---|---|---|---|---|---|---|
| % finer (sand) | 100 | 100 | 100 | 100 | 73.72 | 4.87 |
| % finer (silty clay) | 100 | 100 | 100 | 100 | 62.57 | 24.29 |

**Table 3 Cohesion, angle of shearing resistance, $N_q$ and ultrasonic P wave velocity variation with silty clay content for Pilani region soil**

| Silty clay content (%) | Cohesion (kPa) | Angle of shearing resistance (deg.) | Soil type | $N_q$ | Ultrasonic P wave velocity (m/s) |
|---|---|---|---|---|---|
| 10 | 2.687 | 35 | Cohesion-less | 33.3 | 340 |
| 30 | 8.453 | 22.5 | Inter med-iate | 8.53 | 376.1 |
| 50 | 11.336 | 13 | Inter med-iate | 3.352 | 448.5 |
| 70 | 14.121 | 9 | Inter med-iate | 2.29 | 510.5 |
| 90 | 11.052 | 29 | Inter med-iate | 16.852 | 459.4 |

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## 3. Calibration Curve

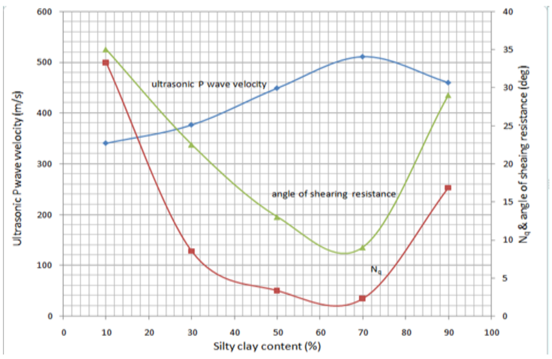


**Figure 1 Ultrasonic P wave velocity, $N_q$ & angle of shearing resistance variation with silty clay content**

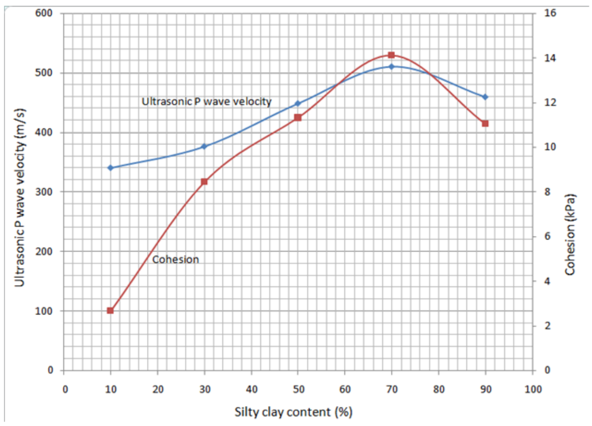


**Figure 2 Ultrasonic P wave velocity & Cohesion variation with silty clay content**

Variation of ultrasonic P wave velocity, angle of shearing resistance and bearing capacity factor $N_q$ with silty clay content has been shown in Figure 1. Similarly variation of ultrasonic P wave velocity and cohesion with silty clay content has been shown in Figure 2. From ground surface till about 5meters depth, soil profile is about the same in Pilani region. Furthermore, this soil is mixture of soil from ground surface and soil from 12 to 15meters depth (Kumar, 2025b). As most of foundation construction is in this depth zone in the region, its net ultimate bearing capacity information is always required when it comes to safe geotechnical design. One can take soil sample from required depth of aforementioned region (up to 5meters depth), oven dry it and sieve it through 300micron sieve. Through transmission ultrasonic testing can be done on this soil sample at 10% water content to obtain P wave velocity. If this velocity is less than 459.4m/s, bearing capacity factor $N_q$ and angle of shearing resistance can be obtained from Figure 1. Similarly cohesion can be obtained from Figure 2. If this velocity is more than 459.4m/s, additional sieving through 150micron sieve will be required to get exact silty clay content. Estimated value of angle of shearing resistance and $N_q$ from Figure 1 as well as cohesion from Figure 2 can still be obtained. As long as cohesion is less than 5kPa (cohesion-less soil), general shear failure is assumed for $\phi \geq 36^0$ and local shear failure for $\phi \leq 29^0$. For intermediate values of angle of shearing resistance, linear interpolation between general and local shear failure is assumed. In the present study, silty clay content of 10% to 90% has been taken. It covers most of the site soils of the region and either local shear failure or linear interpolation between general as well as local shear failure is applicable because soil is cohesion-less. For local shear failure, bearing capacity factors $N'_c$, $N'_q$ and $N'_\gamma$ are required. $N'_q$ can be determined using technique descried in Introduction section. $N'_c$ and $N'_\gamma$ can be obtained from equation (5) and equation (6) respectively. For linear interpolation between general and local shear failure, bearing capacity factors $N_c$, $N_q$, and $N_\gamma$ as well as $N'_c$, $N'_q$ and $N'_\gamma$ are required. $N_q$ and angle of shearing resistance can be obtained knowing experimentally obtained ultrasonic P wave velocity from Figure 1. For the obtained angle of shearing resistance, $N_c$ and $N_\gamma$ can be obtained from equation (3) and equation (4) respectively. $N'_q$ can be determined using technique descried in Introduction section. $N'_c$ and $N'_\gamma$ can be obtained from equation (5) and equation (6) respectively. For intermediate soil mixtures of present study, failure strain was found to be less than 5% and general shear failure was applicable. Estimated value of $N_q$ and angle of shearing resistance can be obtained knowing experimentally obtained ultrasonic P wave velocity from Figure 1. $N_c$ and $N_\gamma$ can be obtained from equation (3) and equation (4) respectively. Figure 1 and Figure 2 thus can be used as calibration curve to obtain estimated value of bearing capacity factors in order to determine net ultimate bearing capacity

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which is an important parameter in foundation engineering. Estimated value of bearing capacity factors can be obtained based on experimentally obtained ultrasonic P wave velocity as described in present study for Pilani region. Ultrasonic P wave velocity through soil can be determined using through transmission technique in laboratory requiring very simple experimental setup.

## Conclusion

Net ultimate bearing capacity determination involves bearing capacity factors for general and/or local shear failure. For most of the sites, their determination requires drained direct shear testing, undrained triaxial testing or unconfined compression testing depending upon soil condition at site. Undrained triaxial testing requires most complicated experimental setup, then drained direct shear testing and then unconfined compression testing. Ultimately experimental setup is complicated in all. In the present study, calibration curve has been developed to obtain estimated value of bearing capacity factor $N_q$, cohesion and angle of shearing resistance based on ultrasonic P wave velocity through soil as a function of particle size composition for Pilani region soil. From ground surface till about 5meters depth, soil profile is about the same in Pilani region[21]. One can take soil sample from required location as well as depth, oven dry it and sieve it through 300micron sieve. Ultrasonic P wave velocity through this soil can be determined using technique described in present study using through transmission technique. If this velocity is less than 459.4m/s, cohesion from Figure 2, as well as $N_q$ and angle of shearing resistance from Figure 1 can be directly obtained. If this velocity is more than 459.4m/s, additional sieving through 150micron sieve will be required to get exact silty clay content. Estimated value of angle of shearing resistance and $N_q$ from Figure 1 as well as cohesion from Figure 2 can still be obtained. Sieving through 75micron sieve will provide the information that weather the soil is cohesive or not. Bearing capacity factors $N_c$ and $N_\gamma$ can be obtained from equation (3) and equation (4) respectively. Bearing capacity factor $N'_q$ can be obtained using technique described in the Introduction section. $N'_c$ and $N'_\gamma$ can be obtained from equation (5) and equation (6) respectively. Ultrasonic P wave velocity determination using through transmission technique requires very simple experimental setup. In a particular region till substantial extent and depth, soil's grain size distribution is about the same. Soil could be cohesive, intermediate or cohesion-less type. As in present study, similar calibration curves can be developed for other region soils also. Technique will cover most of the regions.

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