Seismic Site Classification for Structural Engineers

by Dominic Kelly

Many states and municipalities have adopted the International Building Code (IBC) and, by reference, the seismic provisions in *Minimum Design Loads for Buildings and Other Structures* (ASCE 7-02 and ASCE 7-05). As engineers use these documents, they are beginning to realize how dependent the magnitude of the design earthquake force is on the site class. In seismic provisions of previous model building codes other than the 1997 UBC, the soil type impacted the force level for mid-rise and high-rise buildings, but generally did not affect the seismic design force for low-rise buildings. The site classes in the IBC, ASCE 7-02, and ASCE 7-05 directly impact the seismic design force for all buildings, whether a low-rise or high-rise building. In regions of low or moderate seismicity, a difference in site class may change the seismic design category (SDC), resulting in a difference in design and detailing requirements.

Substantial differences in seismic design force and detailing requirements based on the site class are consistent with observed earthquake damage. Typically, buildings on soft or loose soils sustain substantially more damage than comparable buildings on stiff soil or rock sites.

Although geotechnical engineers typically classify sites, understanding how sites are classified is valuable to a structural engineer's practice. A structural engineer can check a geotechnical engineer's classification, counsel clients when additional work is advisable to classify a site less conservatively, and classify a site for additions when adequate information is available from existing borings.

Basis for Site Classification

The source document for the site classifications defined in the IBC, ASCE 7-02, and ASCE 7-05 is *NEHRP Recommended Provisions for Seismic Regulations for New Buildings and Other Structures* (FEMA 450). Information regarding the basis for the site classifications is provided in its commentary. The commentary describes how soil deposits amplify the level of ground shaking relative to the level of shaking of bedrock. The amount of ground-motion amplification depends on wave-propagation characteristics of the soils, which can be estimated from the measurements of the shear-wave velocity. Soft soils with slower shear-wave velocities generally produce greater amplification than stiff soils with faster shear-wave velocities. The site classes of the IBC, ASCE 7-02, and ASCE 7-05 are defined in terms of shear wave velocity.

Site Class Definitions

The IBC and ASCE 7-02, and ASCE 7-05 define six site classes, Site Class A to Site Class F, based on the upper 100 feet of soil and rock from the base of a building. Base is defined as "the level at which the horizontal seismic ground motions are considered to be imparted to the structure." In almost all cases, the base is the ground level of the building. The commentary to FEMA 450 states: "Conversely, for structures with basements supported on firm soils or rock below soft soils, it is reasonable to classify the site on the basis of the soils for rock below the mat, if it can be justified that the soft soils contribute very little to the response of the structure." In taking advantage of this, consideration needs to be given as to whether the ground level should be treated as an elevated level, which would increase the seismic force on the building.

Descriptions of the site classes defined in ASCE 7-02 and ASCE 7-05 are provided in *Table 1*, along with the definition in terms of shear wave velocity.

Classifying Rock Sites

Site Classes A and B are rock sites, and Site Class C is sometimes assigned to rock sites. Site Class A sites, hard rock, are generally east of the Rocky Mountains. Measured shear wave velocities at the site, or at a site of the same rock type with similar or less severe weathering and fractures, are required to assign Site Class A. Competent rock sites in the West Coast are typically Site Class B. Site Class B may be assigned to any competent rock site with moderate fracturing and weathering, based on either measured or estimated shear wave velocities. Soft rock and highly fractured and weathered rock must be assigned Site Class C, unless measured shear wave velocities demonstrate that Site Class B is applicable. If there is more than 10 feet of soil between the rock surface and the bottom of the spread footing or mat foundation, Site Classes A and B shall not be assigned to the site.

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Table 1 – Site Class Definitions from ASCE 7-02 and ASCE 7-05

Site Class	Site Profile Name	Soil Shear Wave Velocity, v_s (ft/sec)	Standard Penetration Resistance, $\bar{N}$ or Nch	Undrained Shear Strength, $\bar{S}_u$ (psf)
A	Hard rock	$\bar{v}_s > 5{,}000$	NA	NA
B	Rock	$2{,}500 < \bar{v}_s \le 5{,}000$	NA	NA
C	Very dense soil and soft rock	$1{,}200 < \bar{v}_s \le 2{,}500$	> 50	> 2,000 psf
D	Stiff soil	$600 < \bar{v}_s \le 1{,}200$	15 to 20	1,000 to 2,000 psf
E	Soft clay soil	$\bar{v}_s \le 600$	<15	<1,000psf
		Any profile with more than 10 ft of soil having the following characteristics: • Plasticity index PI > 20 • Moisture content $w \ge 40\%$, and • Undrained shear strength $S_u < 500$ psf		
F	Soil requires site response analysis	Liquefiable soils, peat, high plasticity clay		

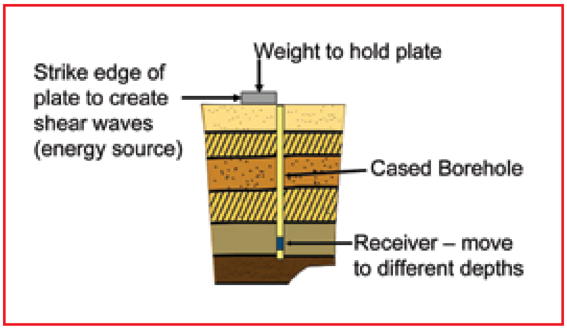

Figure 1 Seismic Down-Hole Test

Classifying Soil Sites

Although the site class descriptions are for a single type of soil or rock type, most sites consist of multiple layers of soil and rock. In classifying a site, all soil and rock layers in the upper 100 feet of the site profile are considered. Sites consisting predominately of very dense glacial tills, sands, gravels, and soil sites with very shallow rock often qualify as Site Class C. When shallow foundations are allowed for a building on a soil site, Site Classes C and D are generally applicable, with Site Class D being more common. When deep foundations are required, the applicable site class is generally Site Class E, though some sites with relatively shallow deep foundation elements, on the order of 30 feet or less, will sometimes qualify as Site Class D. When a site has soils susceptible to collapse during an earthquake, such as liquefiable soils, quick and highly sensitive clays, and collapsible weakly cemented soils, Site Class F is applicable. Site Class F requires a site specific response spectrum analysis to assess the ground motion amplification of the site, except when the fundamental periods of the building are less than 0.5 seconds and the presence of liquefiable soils is the reason for the assigning Site Class F. For a default site class, ASCE 7-02 and ASCE 7-05 state: "Where the soil properties are not known in sufficient detail to determine the site class, Site Class D shall be used unless the authority having jurisdiction or geotechnical data determines Site Class E or F soils are present at the site."

When competent rock is encountered before reaching the bottom of the upper 100 feet of site profile, it is usually acceptable to treat the remainder of the profile the same as the first encountered competent rock. A rare exception to this is for sites with geologically recent volcanic rock that is over soil. Such sites exist in Hawaii.

ASCE 7-02 and ASCE 7-05 include three procedures to assign Site Classes C, D, and E based on the following:

- Average shear wave velocity
- Average field standard penetration resistance
- Average undrained shear strength

Average Shear Wave Velocity Procedure

The most accurate site classification is obtained using the average shear wave velocity procedure, because the site classes are defined based on measured shear wave velocity. A weighted average shear wave velocity is used to account for the greater site amplification that occurs in relatively softer or looser soils with slower shear wave velocities. The weighted average shear wave velocity is obtained using the following:

$$\bar{v}_s = \frac{\sum_{i=1}^{n} d_i}{\sum_{i=1}^{n} \frac{d_i}{v_{si}}}$$

d_i is the thickness of any layer between 0 and 100 feet.

v_{si} is the shear wave velocity in feet/second.

$\sum_{i=1}^{n} d_i$ is equal to 100 feet.

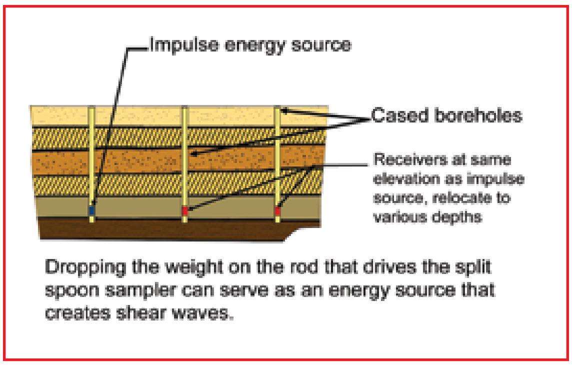

Figure 2 Seismic Cross-Hole Test

Measuring shear wave velocity adds cost to a geotechnical investigation, so most sites are classified using one of the other two procedures. However, the greater accuracy of the average shear wave velocity procedure over that of the average field standard penetration resistance, or average undrained shear strength procedure, can be worth the added cost if its use results in a different site classification. The more favorable site classification will lead to lower design forces, and perhaps even a less severe seismic design category. The resulting savings in cost of a building's structure, and perhaps savings in the anchorage and bracing of architectural and mechanical components, can far exceed the costs required to measure the shear wave velocity.

Four tests are available for measuring shear wave velocity for the purposes of classifying a site:

- Seismic Down-Hole Test
- Seismic Cone Test
- Seismic Cross-Hole Test
- Surface Wave Tests

The seismic down-hole test is the most common test for measuring shear wave velocity for the purposes of classifying a site. It requires a single cased borehole, an impulse energy source at the surface, and a movable receiver or a string of receivers as represented in *Figure 1*. The travel time of shear waves is measured to various depths, and a travel time versus depth curve is generated. Interpretation of the speed is more difficult when ground water is present, but it does not preclude the use of the down-hole test.

The seismic cone test is similar to the seismic down-hole test. A receiver is placed above the friction sleeve of a conventional cone penetrometer. At various depths, penetration is momentarily stopped and an impulse is generated at the surface. The travel time of shear waves is measured to various depths, and a travel time versus depth curve is generated. Cone penetrometers cannot be advanced through very stiff and very dense soil layers, or through gravels and boulders, without damaging the equipment. In areas that have a prevalence of these soil types, such as the Northeast, the seismic cone test is not used extensively.

The seismic cross-hole test is the second most commonly used test for measuring shear wave velocity. It requires a minimum of two and preferably three or more boreholes, an impulse energy source within a borehole, and receivers at the other boreholes as represented in *Figure 2*. Because multiple boreholes are required, a seismic cross-hole test is more expensive than a seismic down-hole test. Seismic cross-hole tests are generally used to measure shear wave velocities for sites with critical facilities, such as nuclear power plants or large dams; they are rarely used for typical building sites. The impulse energy source and receivers are set at the same elevation, and the shear wave velocity is measured at that elevation. By measuring the shear wave velocity at multiple elevations, a shear wave velocity profile can be generated. Care must be taken to avoid over-estimating the shear-wave velocity of a soft or loose layer adjacent to a stiff layer. In this case, the shear-waves can travel from the soft layer to the stiffer layer and back into the soft layer, arriving at the receiver faster than the shear waves that travel directly through the soft layer.

Several surface wave tests are also available to measure shear wave velocity. The most common surface wave test is the spectral analysis of surface waves (SASW) test represented in *Figure 3*. These tests require an impulse

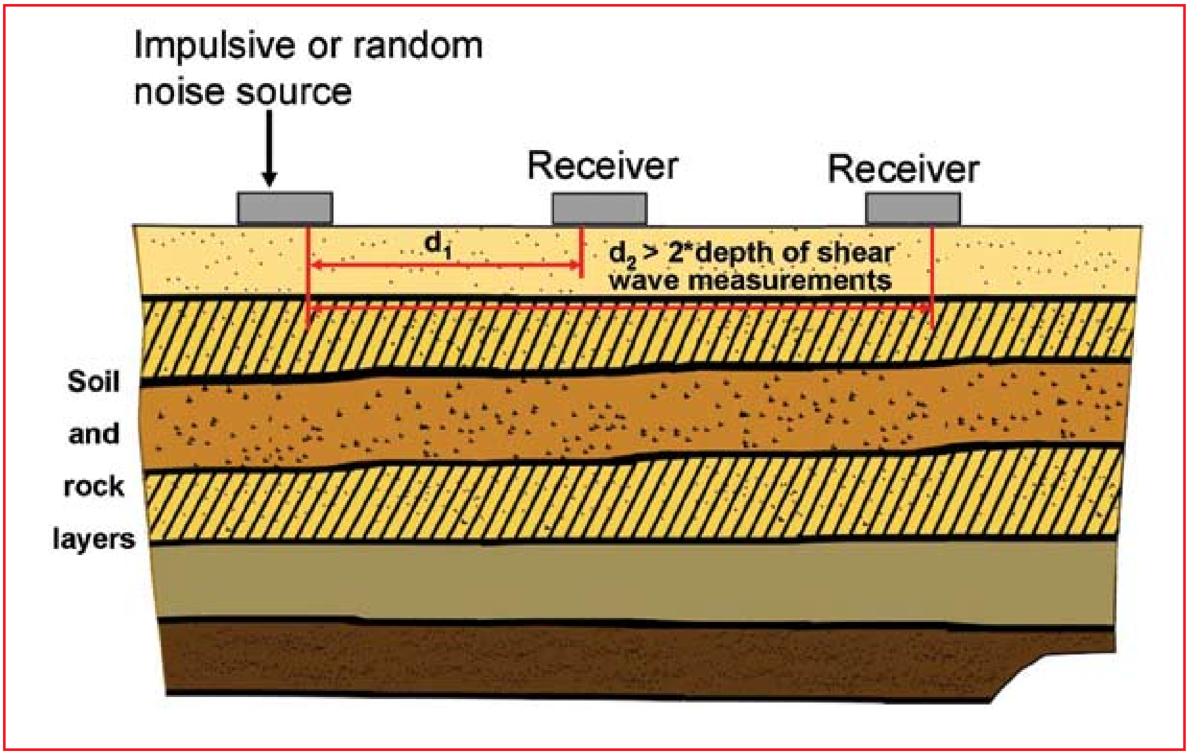

Figure 3 Spectral Analysis of Surface Waves Test (SASW)

source and receivers on the surface. These tests are good for locations where boreholes cannot be drilled. There are some limitations as to the sites where these tests can be performed. The tests are difficult to perform in an urban environment, although it may be possible in a large basement of a building. To obtain accurate shear wave velocities, the equipment should only be used by operators with expertise in the test method. At this time, there is limited commercial availability of these tests, and they have generally been used at critical facilities. However, surface wave tests are inexpensive and hold great promise for classifying sites in the future.

Average Standard Penetration Resistance Procedure

The most commonly used procedure for classifying a site is the standard penetration resistance procedure. This procedure requires little or no additional field investigation than geotechnical engineers typically provided in the past. Generally, only one boring is extended to a depth of 100 feet and the other borings are extended to depths as required to make foundation support recommendations.

This procedure is, by design, conservative because the correlation between site amplification and standard penetration resistance is more uncertain than the correlation between site amplification and shear wave velocity. It is most conservative for sites with substantial layers of cohesive soils.

A weighted average standard penetration resistance is used to account for the greater site amplification that occurs in softer or loose soils. The weighted average standard penetration resistance is obtained using the following:

$$\bar{N} = \frac{\sum_{i=1}^{n} d_i}{\sum_{i=1}^{n} \frac{d_i}{N_i}}$$

d_i is the thickness of any layer between 0 and 100 feet.

N_i is the standard penetration resistance blows/foot for the layer.

$\sum_{i=1}^{n} d_i$ is equal to 100 feet.

The standard penetration resistance procedure is presented in ASCE 7-02 in a manner that has led some engineers to conservatively exclude rock layers within the upper 100 feet of the site profile. Excluding the rock can lead to a less favorable and unrealistic site classification. ASCE 7-05 is clear that all layers within the upper 100 feet are included. When rock or very stiff soil layers with N_i greater than 100 blows/foot are encountered, N_i for those layers is to be taken as 100 blows/foot.

ASCE 7-05 states the standard penetration resistance is to be as directly measured in the field without corrections. Based on comments made by Lawrence F. Johnsen of Heller and Johnsen, Francis Leathers of GEI Consultants, and Kenneth Stokoe of the University of Texas at Austin, the author believes the intent is to not correct field measured standard penetration resistance for soil overburden pressures, but to normalize standard penetration resistance to a hammer energy ratio of 60%. The rope and cathead safety hammers have energy ratios of 55 to 65%. Energy ratios for the old fashioned donut hammers are 35 to 45%, and the energy ratio for newer automatic safety hammers varies by manufacturer with typical ratios being 75 to 85%. (*Refer to sidebar, "Standard Penetration Test Energy Measurements" by Lawrence F. Johnsen for a description on how Standard Penetration test energies are measured.*) The author understands that ASCE 7 Seismic Task Committee will address correcting field measured standard penetration resistances for hammer energy as new business for the next version of ASCE 7.

Average Undrained Shear Strength

This procedure is, by design, conservative because the correlation between site amplification and undrained shear strength is more uncertain than the correlation between site amplification and shear wave velocity. However, for sites with substantial deposits of cohesive soils, this procedure is generally less conservative than the average standard penetration resistance method.

In using the average undrained shear strength procedure, the cohesive and cohesionless soils must be treated separately. Thus two formulae must be used, and two site classes must be determined.

For the cohesive soil layers, the weighted average undrained shear strength is obtained using the following:

$$\bar{S}_u = \frac{d_c}{\sum_{i=1}^{k} \frac{d_i}{S_{ui}}}$$

$d_c = \sum_{i=1}^{k} d_i$, where k is the number of cohesive soil layers and d_c is the total thickness of cohesive soil layers.

S_{ui} is the undrained shear strength in psf of a cohesive layer, not to exceed 5,000 psf.

The weighted average undrained shear strength of the cohesive soil layers is used with the criteria in *Table 1* to assign a site classification.

For the cohesionless soil layers, the weighted average standard penetration resistance is obtained using the following:

$$\overline{N}_{ch} = \frac{d_s}{\sum_{i=1}^{m} \frac{d_i}{N_i}}$$

$d_s = \sum_{i=1}^{m} d_i$, where m is the number of cohesionless soil layers and d_s is the total thickness of cohesionless soil layers.

N_i is the standard penetration resistance blows per foot for the cohesionless soil layers.

The weighted average standard penetration resistance is compared with the criteria in *Table 1* to assign a site classification for the cohesionless soil layers.

The site classifications for the cohesive and cohesionless soil layers are compared and the classification with the lower shear wave velocity is assigned to the site. This procedure can be very conservative when substantial rock is in the 100 foot profile, the cohesive soil layers are soft and not very thick, or when the cohesionless layers are loose and not very thick.

Summary

With an understanding of how site classes are assigned, structural engineers will be in a position to make valuable recommendations to their clients. Because the structural engineer determines seismic design forces and establishes the seismic design category, he or she is in a better position than the geotechnical engineer to identify how significant an impact the site classification makes on the design and cost of the building. If the structural engineer recognizes that a change in site class to the next class with a higher shear wave velocity will change the seismic design category or significantly lower the design force, he or she can advise their client to undertake additional geotechnical investigations, such as classifying the site using shear wave velocities instead of using the standard penetration resistances.▪

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References

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Standard Penetration Test Energy Measurements

By Lawrence F. Johnsen, P.E.

Today, equipment is readily available to measure the energy transfer from a Standard Penetration Test (SPT) to the drill string. The method most commonly used is the Force Velocity method in which force and velocity are integrated over time.

Equipment typically consists of a pile driving analyzer, which is connected to an instrumented drill rod that contains two strain gages and two accelerometers. The instrumented drill rod section (*shown in the photo below*) is placed at the top of the drill string.

Energy transfer measurements are made for every hammer drop during an individual SPT test. Tests are performed on several but not all SPT tests. The attachment of the instrumented rod section adds about 15 minutes to the driller's time for each test. A typical report includes a tabulation of energy measurements for each hammer drop, along with the average energy transfer and coefficient of variation for each SPT test.▪

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Attaching SPT to Instrumented Rod Section