SEISMIC SITE CLASSIFICATION IMPROVEMENT USING GEOPIER SOIL REINFORCEMENT

This Technical Bulletin discusses the seismic design portions of the 2000 International Building Code (IBC) adopted in many areas of the United States. This bulletin focuses on the geotechnical site classifications used for establishing response spectra and describes the use of Geopier® soil reinforcing elements to stiffen site soils, thereby improving the site classification and reducing design level accelerations.

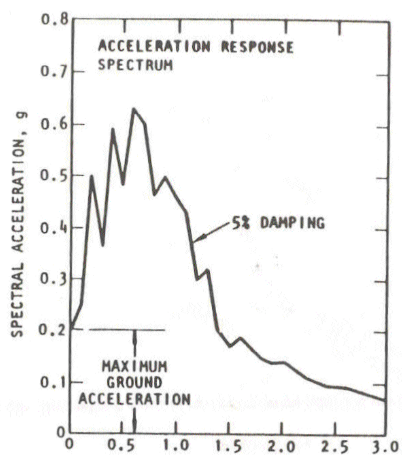
1. GROUND MOTION BACKGROUND OF THE 2000 IBC

Earthquakes cause the surface of the earth to accelerate randomly in three dimensions. The vibrations that reach the surface from the underlying rock depend on the overlying soil constituents. Typically, most structures constructed on or near the ground surface are designed to resist only the horizontal components of ground accelerations; vertical accelerations are usually ignored. One of the most common and straightforward methods engineers use to design structures for seismic-induced accelerations is the Equivalent Lateral Force Method, whereby complicated and random ground motions from earthquakes are simplified and reduced to an equivalent static force. Generally speaking, the magnitude of the equivalent lateral force is a function of the mass of the structure, its fundamental period of vibration, the proximity of earthquake source(s), damping characteristics, and local soil conditions. The lateral force is roughly equivalent to mass times acceleration.

RESPONSE SPECTRUM

When a structure's base is subjected to horizontal ground motions, it responds by swaying. A tool that engineers use to relate a structure's response to its fundamental period of vibration is a graph called a response spectrum. A response spectrum plot can relate displacement, velocity, or acceleration to fundamental period for a given ground motion or set of ground motions. Thus, the response of a structure across a spectrum of periods can be plotted. Figure 1 gives a plot of the acceleration response vs. period for a hypothetical earthquake ground motion. For example, for a structure with a fundamental period of 0.5 second, subjected to this particular ground motion, the maximum acceleration response would be about 0.5g, or five tenths of gravity.

Figure 1.
Typical Spectral Acceleration vs. Period Plot for a Hypothetical Earthquake.



PEAK GROUND ACCELERATION VS. SPECTRAL ACCELERATION

Referring again to Figure 1, note that the maximum acceleration of the ground surface, or Peak Ground Acceleration (PGA), is approximately 0.2g represented by the response spectra value at a natural period of zero. For structures with periods up to about 1.5 seconds, the spectral acceleration of the structure is greater than or equal to the PGA and for structures with periods greater than about 1.5 seconds, the spectral acceleration of the structure is less than the PGA. This would be for a single, hypothetical earthquake. The design response spectra given in the building codes are intended to include a multitude of potential earthquakes that could affect a given site.

STRUCTURAL DAMPING

When building structures are set in motion caused by ground accelerations, they tend to return to their starting position quickly once the input motion ceases (assuming elastic behavior). Damping is the property of a structure that prevents indefinite oscillations to occur. Critical damping is defined as that value of damping that would prevent oscillation from taking place. In other words, a critically damped structure, if plucked, would return to its original position with no oscillations. An idealized structure with zero damping (and no other energy losses due to friction, ductility, etc.) would oscillate indefinitely if plucked. Real building structures are damped by virtue of their material characteristics, connections, non-structural elements, and many other factors. Empirically, building damping is generally assumed to be in the range of 2% to 15% of critical damping, with 2% to 5% being the common values used. When structural damping is considered, the general shape of the response spectrum remains the same, but it is scaled downward (except at zero period).

CHANGES IN THE CODE

The 2000 International Building Code (IBC) incorporates a new methodology used to determine the probable earthquake-induced ground motions at a particular site. Prior codes were based on outdated knowledge of earthquake ground motions. Over the last 25 years, significant additional earthquake data has been obtained. The 2000 IBC is based on the 1997 FEMA 302, which is based on new seismic hazard maps developed for the United States by the US Geological Survey (USGS) in the mid 1990s.

The IBC represents the maximum considered earthquake (MCE) ground motion at a particular geographic location using spectral acceleration response maps. The MCE is defined as a ground motion with a 2% probability of being exceeded in 50 years (2500-year return period). Two separate maps were generated; one for structures with short periods (0.2 seconds was selected to represent the short period range of the response spectral value for the entire U.S.) and one for structures with a one second period, both assuming 5% of critical damping. Recognizing the inherent factors of safety in the design provisions of the Code, two-thirds of the mapped spectral values may used for design. With these two values, scaled up or down for site effects, a design response spectrum can be constructed that represents the spectral response of a structure at that location.

Figure 2 shows the generalized design response spectrum from the IBC. S_{DS} is the design spectral acceleration at short periods and S_{D1} is the design spectral acceleration at one-second periods. The point T_0 is defined in the IBC as $0.2S_{D1}/S_{DS}$ and Ts is S_{D1}/S_{DS}. The equation of the line for periods shorter than T_0 is given as $S_a = 0.6\ S_{DS}/T_0 + 0.4S_{DS}$.

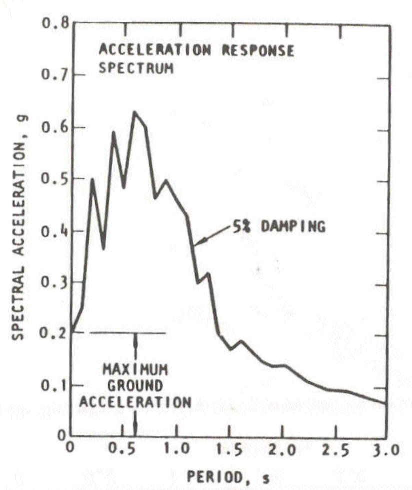


Figure 2.
IBC Design Response Spectrum.

INFLUENCE OF SOIL STIFFNESS ON STRUCTURAL RESPONSE

The IBC defines five site classifications, A through F, based on the types of soil/rock profile and their engineering properties. The stiffness of the soil beneath a building influences the spectral acceleration experienced by the building structure. In general, softer soil conditions tend to amplify the ground motions. These concepts are embodied in Tables 1615.1.2(1) and 1615.1.2(2) in the 2000 IBC. The design response spectrum given in the IBC was developed for a site class B, so the spectral response values for sites other than class B must be multiplied by the appropriate site coefficient given in the tables. Coefficients range from 0.8 for site class A to as high as 3.5 for site class E. (Note that a site-specific geotechnical investigation is required by the IBC for site class F).

Thus, for a building designed on a softer soil site, the design spectral acceleration would generally be higher than it would be for a site with firmer soil. Because of the relationship between force and acceleration, buildings that are designed for greater spectral accelerations will be subjected to greater design forces, requiring larger structural members, stronger connections, and special considerations regarding anchorage of non-structural components, all of which translate to higher cost of construction.

2. BUILDING CODE MODIFICATIONS

The implementation of the 2000 International Building Code has generally resulted in an increase in the spectral acceleration values used for design, in comparison to the previously used Building Officials Code Association (BOCA) recommendations. Because base shear force is the product of building mass and spectral acceleration, the code changes have resulted in larger design values used to compute the loading demands on structures.

EXAMPLE: WASHINGTON, D.C.

Graphical comparisons of spectral acceleration values in Washington D.C. using the 1997 BOCA code and the 2000 IBC code are shown in Figures 3 and 4. Figure 3, for very stiff soil or rock sites, reveals that the spectral acceleration values recommended by the IBC code are slightly lower than those recommended by BOCA. Figure 4, presenting the differences between the IBC and BOCA codes for soft soil sites, illustrates significant increases in spectral acceleration recommended by the 2000 IBC code compared to the previous BOCA code. The spectral acceleration levels for structures with periods of less than about 0.8 seconds (typically structures with eight stories or less) is on the order of two to three times greater with the new code in comparison with the old code. *The changes in the code recommendations have the greatest effect on short buildings overlying soft soils.*

Figure 3.
IBC-BOCA Design Response
Spectra Comparison for
Stiff Soil/Rock Sites.

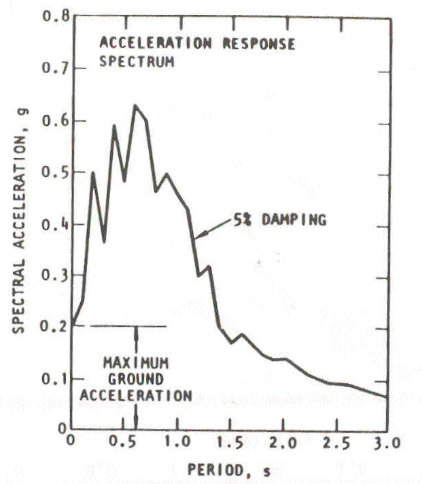
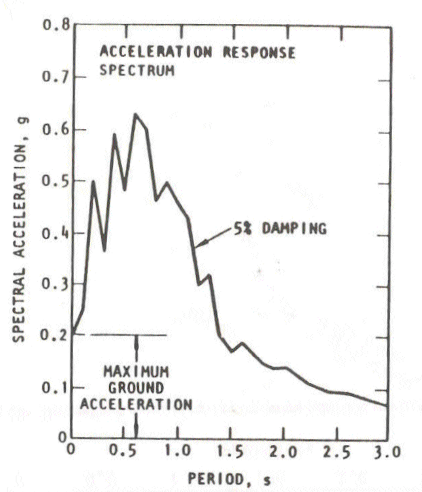


Figure 4.
IBC-BOCA Design Response
Spectra Comparison for
Soft Soil Sites.



AUTOMATIC CLASS E

The 2000 IBC code also mandates that sites with more than ten feet of soft soils must be automatically classified as a Class E (described in more detail below). Soft soils are defined by the code as having undrained shear strengths of less than 500 psf, water content of greater than 40%, and plasticity index of greater than 20.

JUSTIFICATION FOR SOIL SITE CLASS IMPROVEMENT

The increased design accelerations for building founded on soft soil sites, particularly those buildings with eight stories or less, results in significant increases in the structural member sizing to resist the lateral loads as calculated by the building code. The increase in the structural member sizes can have major cost impacts on a project. For these reasons, in certain cases, increasing the stiffness (site class) of a subsurface profile can lead to cost savings in the building's superstructure.

3. EVALUATION OF THE INTERNATIONAL BUILDING CODE SITE CLASSIFICATION

The methods for determining site classification are different in the 1997 BOCA and 2000 IBC codes. The 1997 BOCA code provides a table correlating site classification with simplified soil descriptions. The 2000 IBC code recommendations provide for more rigorous approaches to determine the site classification. The following three approaches to estimate site classification are provided in the IBC code: shear wave velocity approach, SPT N-value approach, and undrained shear strength approach. All three approaches compute the average stiffness of the subsurface profile (whether soil or rock) to a depth of 100 feet below the ground surface and then compare the average stiffness to a benchmark value. The weighted average calculations for the shear wave velocity approach are described by the following equation, where υ_{si} is the shear wave velocity (fps) and d_i is the layer thickness between 0 feet and 100 feet.:

$$\upsilon_s = \frac{\sum_{i=1}^{n} d_i}{\sum_{i=1}^{n} \frac{d_i}{\upsilon_{si}}} \qquad \textit{Eq.1.}$$

The SPT N-value and undrained shear strength approaches rely on the same weighted average calculation approach by simply substituting the SPT N-value or undrained shear strength for each layer, respectively.

BENCHMARK VALUES FOR SITE CLASS

The following information contained in Table 1 is taken from Table 1515.1.1 of the 2000 IBC code and describes the different site classifications based on shear wave velocities, Standard Penetration Test (SPT) N-values, and undrained shear strengths. The weighted average of the selected parameter values calculated for the soil profile is compared to the ranges in Table 1 to arrive at a site class.

Table 1: IBC Code Site Classes

SITE CLASS	SOIL PROFILE NAME	SHEAR WAVE VELOCITY, υ_s IN TOP 100 FEET (ft/s)	STANDARD PENETRATION RESISTANCE, N	SOIL UNDRAINED SHEAR STRENGTH, S_u (psf)
A	Hard Rock	$\upsilon_s > 5{,}000$	Not applicable	Not applicable
B	Rock	$25{,}000 < \upsilon_s \leq 5{,}000$	Not applicable	Not applicable
C	Very dense soil and soft rock	$1{,}200 < \upsilon_s \leq 2{,}500$	$N > 50$	$S_u \geq 2{,}000$
D	Stiff soil profile	$600 < \upsilon_s \leq 1{,}200$	$15 \leq N \leq 50$	$1{,}000 \leq S_u \leq 2{,}000$
E	Soft soil profile	$\upsilon_s < 600$	$N < 15$	$S_u < 1{,}000$

The selection of the most appropriate approach to evaluate the site class depends on the availability of site specific data and the soil conditions. The following discussion presents useful correlations to estimate the site class using the shear wave velocity approach.

SHEAR WAVE VELOCITY OF GEOPIER RAMMED AGGREGATE PIERS

The shear modulus of cohesionless soil may be determined from in-situ measurements or from the following correlations with SPT N-values:

$$G_{max} = 20{,}000(N_1)_{60}^{0.333}(\sigma'_m)^{0.5} \qquad \textit{Eq.2.}$$

[Seed et al. 1986]

$$G_{max} = 325\ N_{60}^{0.68} \qquad \textit{Eq.3.}$$

[Imai and Tonouchi 1982]

where $(N_1)_{60}$ is the SPT N-value corrected for energy and overburden, σ'_m is the mean effective stress, and N_{60} is the SPT N-value corrected for energy. G_{max} and σ'_m are in units of pounds per square foot (psf). The shear wave velocity may be calculated using the results of the shear modulus calculations provided in Equations 2 and 3 and the unit weight as shown below:

Eq.4.

$$\upsilon_s = (G/\rho)^{0.5}$$

where ρ is equal to the unit weight of the soil (density divided by gravitational coefficient of 32.2 ft/s^2)

SHEAR WAVE VELOCITY OF GEOPIER RAMMED AGGREGATE PIERS

Research performed at Iowa State University to develop measurements of shear wave velocity values within Geopier Rammed Aggregate Piers using geophones to record shear wave propagation through the pier. The results of the research indicate shear modulus values on the order of 6,300 ksf (White 2004). Using the relationship shown in Equation 4, shear wave velocities of 1,200 ft/s are calculated for the installed pier.

4. USE OF GEOPIER SOIL REINFORCEMENT TO IMPROVE SITE CLASSIFICATION

As shown in the previous examples (Figures 3 and 4), sites containing stiffer soil profiles classify as having site classes that result in a decrease in design-level spectral acceleration for short buildings (less than eight stories tall). Geopier Rammed Aggregate Piers™ may be used to stiffen selected layers of soil thereby changing the seismic site classification and reducing spectral acceleration values. Geopier construction is described in detail in the Geopier Reference Manual (Fox and Cowell 1998) and in the literature (Lawton and Fox 1994, Lawton et al. 1994). The elements are constructed by drilling out a volume of compressible soil to create a cavity and then ramming select aggregate into the cavity in thin lifts using the patented beveled tamper. The ramming action causes the aggregate to compact vertically as well as to push laterally against the matrix soil, thereby increasing the horizontal stress in the matrix soil and reducing the compressibility of the matrix soil between the elements. Geopier construction results in very dense aggregate piers with a very high stiffness, yielding a significantly increased composite soil stiffness within the Geopier-reinforced zone.

COMPOSITE SHEAR WAVE VELOCITY WITHIN GEOPIER REINFORCED ZONE

The installation of Geopier Rammed Aggregate Piersincreases the composite shear wave velocity of the soil layers reinforced by the piers. The composite shear wave velocity within the Geopier-reinforced zone ($\upsilon_{s,\ comp}$) is calculated using the following relationship

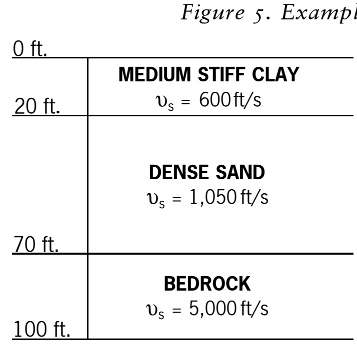
$$\upsilon_{s,\ comp} = (R_a)\ \upsilon_g + (1 - R_a)\ \upsilon_s \qquad \textit{Eq. 5.}$$

where υ_g is the Geopier shear wave velocity value, υ_s is the shear wave velocity of the matrix soil in the Geopier-reinforced zone, and R_a is the Geopier area ratio. The Geopier area ratio is the ratio of the Geopier cross-sectional area coverage to the total area.

5. EXAMPLE

The following example illustrates the approach to determine the soil site classification for the unreinforced soil profile shown in Figure 5 and the site classification incorporating Geopier Rammed Aggregate Piers.

Figure 5. Example Profile.



UNREINFORCED SITE CLASSIFICATION

From 2000 IBC, the weighted average shear wave velocity is calculated as shown below:

Eq.6.

$$\upsilon_{s\text{-avg}} = \frac{\sum_{i=1}^{n} d_i}{\sum_{i=1}^{n} \frac{d_i}{\upsilon_{si}}} = \frac{100\text{ ft}}{\frac{20\text{ ft}}{600\text{ ft/s}} + \frac{50\text{ ft}}{1{,}050\text{ ft/s}} + \frac{30\text{ ft}}{5{,}000\text{ ft/s}}} = 1{,}150\text{ ft/s}$$

The results of the calculation indicate an average shear wave velocity for the upper 100 feet of the profile is 1,150 ft/s. Using a value of 1,150 ft/s, Table 1 yields a Site Class D.

GEOPIER -REINFORCED SITE CLASSIFICATION

$$\upsilon_{s\text{-avg}} = \frac{\sum_{i=1}^{n} d_i}{\sum_{i=1}^{n} \frac{d_i}{\upsilon_{si}}}$$

Eq.7.

If the medium-stiff clay layer is reinforced with Geopier Rammed Aggregate Piers at an area ratio of 15%, the composite shear wave velocity in the upper 20 feet would be equal to the following:

Eq.8.

$$\upsilon_{s\text{-comp}} =$$

$$R_a\,(\upsilon_g) + (1 - R_a)\upsilon_s = (0.15)(1{,}200)\text{ ft/s}) + (1 - 0.85)(600\text{ ft/s}) = 690\text{ ft/s}$$

The average shear wave velocity for the site using the composite shear wave velocity for the Geopier-reinforced zone becomes:

Eq.9.

$$\upsilon_{s\text{-avg}} = \frac{100\text{ ft}}{\frac{20\text{ ft}}{690\text{ ft/s}} + \frac{50\text{ ft}}{1{,}050\text{ ft/s}} + \frac{30\text{ ft}}{5{,}000\text{ ft/s}}} = 1{,}210\text{ ft/s}$$

The installation of Geopier Rammed Aggregate Piers at an area ratio of 15% (approximate spacing of seven feet on-center) increases the average shear wave velocity from 1,150 ft/s to 1,210 ft/s. Based on this improvement the site class may be increased from Site Class D to Site Class C.

6. SUMMARY

The adoption of the 2000 IBC has resulted in changes in the seismic design levels for many structures. Geopier soil reinforcement may be used to stiffen soil layers, thereby increasing the shear wave velocity and raising the seismic site class for design. Increasing the seismic site class reduces the design-level spectral acceleration values and reduces the cost of the superstructure.

REFERENCES

Building Officials and Code Administrators International, Inc., 1997. BOCA Building Code. Country Club Hills, IL.

FEMA, 1997, “NEHRP Recommended Provisions for Seismic Regulations for New Buildings and Other Structures,” Part 1: Provisions (FEMA 302). 1997 Edition.

Fox, N.S. and Cowell, M.J., 1998, Geopier Foundation and Soil Reinforcement Manual, Geopier Foundation Company, Inc., Scottsdale, AZ.

Imai, T. and Tonoghi, K., 1982, “Correlation of N-value with s-wave velocity and shear modulus,”Proceedings, 2nd European Symposium on Penetration Testing, Amsterdam, 57-72.

International Code Council, Inc., 2000. International Building Code. 5th Edition, Falls Church, VA.

Lawton, E.C. and Fox, N.S., 1994, “Settlement of structures supported on marginal or inadequate soils stiffened with short aggregate piers,” Vertical and Horizontal Deformations of Foundations and Embankments, A.T. Yeung and G.Y. Fello (Editors), American Society of Civil Engineers, 2, 962-74.

Lawton, E.C. and Fox, N.S., and Handy, R.L., 1994, “Control of settlement and uplift of structures using short aggregate piers,” In-Situ Deep Soil Improvement, Prod. ASCE National Convention, Atlanta, GA, 121-132.

Seed, H.B., Wong, R.T., Idriss, I.M., and Tokimatsu, K., 1986, “Moduli and damping factors for dynamic analyses of cohesionless soils.” Journal of Geotechnical Engineering. ASCE, Vol. 112, No. GT11, 1016-1032.

White, D.J, 2004, Personal communication. September 8, 2004.

ACKNOWLEDGEMENT

John Miller, P.E., S.E., Principal, KPFF
Brendan T. FitzPatrick, Associate Project Engineer, Geopier Foundation Company, Inc.
Kord Wissmann, Ph.D., P.E., Chief Engineer, Geopier Foundation Company, Inc.

SYMBOLS USED

d_i	=	Layer thickness
G_{max}	=	Maximum shear modulus
ρ	=	Soil unit weight
N_{60}	=	Standard penetration value corrected for energy
$(N_1)_{60}$	=	Standard penetration value corrected for overburden and energy
R_a	=	Ratio of cross-sectional area of Geopier elements to gross footing area
σ'_m	=	Mean effective stress
υ_g	=	Shear wave velocity of Geopier soil reinforcement
υ_s	=	Shear wave velocity of matrix soil
$\upsilon_{s,\ comp}$	=	Composite shear wave velocity

NORTH AMERICA AND SOUTH AMERICA

Geopier Foundation Company
1997 South Main Street, Suite 703
Blacksburg, VA 24060
Telephone: (540) 951.8076 or (800) 371.7470
Fax: (540) 951.8078
Email: info@geopiers.com
www.geopiers.com

EUROPE AND ASIA

Geopier Global Corporation
7600 North 71st Street
Paradise Valley, AZ 85253
Telephone: (480) 998.3522
Fax: (480) 998.3542
Email: natfox@geopierglobal.com
www.geopierglobal.com

Geopier Foundation Company, Inc.

1.800.371.7470
www.geopiers.com