Geotechnical Investigations for Foundation of Multistoried Buildings and Bridges

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Abstract

The paper emphasizes the necessity of carrying out adequate field and laboratory investigations for soil or rock material constituting the foundation of multistoried buildings and bridges. Various stages of investigation, object and method of investigation, required surface and sub-surface explorations, different soil and rock mechanics parameters which have to be determined for designing the suitable and safe foundation have also been described.

Introduction

With the advent of civilization, the man made dwellings and then communication routes. With the advancement in his knowledge he made multistoried buildings and bridges, which need proper foundation. The word 'foundation' is itself very enchanting. Literally it means the base over which some thing is created, hence it deserves due attention or else the entire superstructure would fail.

Karl Terzaghi the father of soil mechanics, once remarked " Foundation can appropriately be described as a necessary evil (Terzaghi, 1943). On account of the fact there is no glory attached to the foundation, and that the source of success or failure are hidden deep in the ground, building foundations have always been treated as step children and their acts of revenge for the lack of attention can be very embarrassing".

The comments made by Terzaghi are very significant and should be taken note of by all concerned. Substructures are as important as superstructures, as such complete understanding of the foundation characteristics must be known in advance. Foundation failure are generally due to yielding of the underlying soil or rock mass, but if the settlement is uniform no serious damage to the structure is expected. Unequal settlements cause secondary stresses in the members, which ultimately lead to the structural failure. The other problems that are encountered can be classed as gravitational (tension) and erosion (Terzaghi and Peck, 1960; Krynine & Judd, 1957)). All this could be avoided if the strata underlying the structure are properly investigated. The necessity of carrying out adequate geo-technical investigations need not be emphasized. The only thing warranting attention is as to how best this can be carried out.

Stages of Investigation

Normally a project is developed in 3 stages, each identified by a word descriptive of the object of each stage.

1. Reconnaissance Stage
2. Feasibility stage
3. Specification stage

The nature of data, objective and scope of each stage is given in table- 1.

Two additional stages carry a project to completion, i.e., Construction Stage and finally Operation and Maintenance.

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Table- 1

Stage	Nature of Data	Objective & Scope
1. Reconnaissance	Descriptive	1. To evaluate the engineering & economic feasibility with in a short period. 2. To assess the general sub-surface conditions existing in the area. 3. To determine the approximate cost & physical ability of constructing the type of proposed structure. 4. To select the most economical & safe plan out of several alternatives.
2. Feasibility	Quantitative	1. To confirm or expand the work done in the reconnaissance stage. 2. To establish a factual background for a safe and economic design & estimate of the cost. 3. Review of the work done during reconnaissance stage. 4. Preparation of program of work for sub-surface explorations. 5. Performance of the explorations. 6. Preparation of the feasibility report.
3. Specification	Primarily quantitative & specific, confirmative	1. To provide data from which design for construction of various features of a project may be made. 2. Programming further exploration.

Object of Geotechnical Investigation

The primary object of Geo-technical investigation is to determine the nature & composition of the soil or rock type and its physical properties, particularly, the strength and deformation characteristics, so that, a safe and economical foundation may be designed for the proposed civil engineering structure.

The information on sub-surface conditions is specially required for virgin areas, where there is lack of previous experience with similar type of structures in the neighborhood. It is very well known that the characteristics of the soil are extremely variable and may change sharply with in limited distance. It is unsafe to assume that conditions found at one site persist beyond the area already explored. In fact, each site should be regarded as a problem in itself and so investigated that there can be no doubt about the capability of the sub-strata for supporting the load to be applied. The empirical relationship and arbitrary building codes are quite often very conservative, some times inadequate and usually not economical hence no longer required.

In short, geo-technical investigation is meant for obtaining information, which will provide a base for the purposes is given in table-2.

Methods of Investigation

The subject of geo-technical investigation is broad in scope. Besides the complexities inherent in the civil engineering itself the sciences of geology, ortho-photography, geophysics, seismology, rock mechanics and soil mechanics are also involved and considered as a part of exploration subject. In addition there are a multitude of details in regard to the mechanics of progressing boreholes

Table- 2

1.	Selecting a suitable site.
2.	Selecting the type and depth of foundation.
3.	Determination of load bearing capacity of the selected foundation.
4.	Prediction of settlement.
5.	Seismic risk.
6.	Effect of atmospheric temperature variation on the foundation, particularly in the permafrost areas.
7.	Stability of hill slopes in the vicinity of the structure.

beneath the surface, for obtaining the samples of materials encountered and of preparing logs, reports and records of field work.

The investigations are conducted in the office, in the field and in the laboratory. The entire procedure can be divided into 3 broad heads, i.e., surface exploration, sub-surface exploration and laboratory tests.

A. Surface Exploration

In surface exploration there are three main attributes:

2. **Geology** is the foundation of the entire procedure and unless there is full usage of this scientific tool, many errors may result hence geological maps are most important.

3. **Air Photos** present an over all perspective of a large area. All features of the landscape, both natural and man made, are recorded and can be studied conveniently with the help of stereo pairs the view becomes 3-Dimensional. It provides useful data regarding topography, drainage, erosion, vegetation, land use, type of structure of rock, i.e., fabric, stratification, fracture pattern etc. It can also give information regarding deformation (settlement, creep, sliding, convergence and dilation).

   These mechanical advantages, this optimum position of the viewer coupled with a through knowledge of geology and pedology provide very useful information.

4. **Geophysics** has provided new and useful tools well adopted for the investigation of many sub-surface explorations. Geophysical methods are used to obtain an initial overall assessment of the site, which can assist in optimizing the site exploration programme.

   Regarding multistoried building and bridge foundation, in addition to obtaining the degree and depth of weathering, the geophysical methods can be used to obtain physical and dynamic properties of rock mass like permeability, degree of compaction and cementation, degree of soundness, degree of decompression, stress field etc.

   Of the geophysical methods available, the seismic refraction and earth resistivity methods of test have proved to be of particular value for rapid sub-surface investigations. They are very attractive and suggest the opportunity to effect savings both in terms of time and money. They make specific measurements of the in-situ physical properties of the strata. Each procedure consists of 3 stages:

   1. Instrumentation
   2. Field Technique
   3. Interpretation

Seismic Refraction Method: It consists of creating sound or vibration waves with in the earth, usually by exploding devices beneath the surface and measuring the time of travel of these waves from their point of origin to each of several detectors (geo-phones) placed a known distances from the source.

Earth Resistivity Method: It is based on the concept that many of the materials making up the earth crust can be identified in some degree at least, by their reaction to the flow of a direct current of electricity. This is an action of electrolytic nature in which, the moisture in the soils and rocks, together with the dissolved impurities gives characteristic resistance to a current flow to several materials.

Both these techniques have their own advantages and limitations. They should be considered as a supplement to more conventional borings. They should not be used with out full appreciation of the technique involved and the necessity to repeatedly check the measurements against observed profiles.

A. Subsurface Exploration

These are performed for 3 purposes:

1. To determine what discrete mass of soil and rock exist in a foundation or borrow area, within the area of interest.
2. What are the dimensions of these bodies?
3. What are their engineering properties?

For structures such as multistoried buildings are bridge piers even a single hole may give lot of information. However, the planning of subsurface exploration programme should include the site plan of the area and the layout plan of the structure to be built with position of columns, expected load on each column, basement floors etc. Preliminary description of bore holes and other field tests to be performed should also be indicated.

Procedure for advancing a hole in the ground is given in table- 3.

The extent up to which, drilling explorations should be carried out varies from 1½ to 2 times the lateral dimension of the foundation below the foundation level. Compact sites for bridges require relatively deep and costly spaced borings, depending upon the type of structure and site conditions. Particular attention should be given to the rock or soil at or just below the foundation level. In certain areas (karstic areas) special precaution may need to be taken by way of locating underground cavities, which may collapse and damage the superimposed structure.

Table- 3

Type	Procedure	General uses
Test pit	Pit may be excavated by hand tools or mechanically	1. Preliminary exploration. 2. For taking hand cut soil samples.
Auger	Operated by hand or power	Auger boring or wash boring are the most common methods for advancing test holes.
Wash boring	Hole advanced by water jet & a chopping bit.	- - - do - - -
Percussion Drill	Jack hammer or the type of drilling equipment, which bore a hole in rock or soil by a chopping bit.	For drilling a hole in rock or hard material.
Rotary Drill	Continuous rock core by means of rotary diamond drill bit attached to core barrel & drill rod.	Common type of bedrock.

For the investigation of the bedrock, the minimum depth of the hole should be 3 to 5 m into sound rock. The lateral extent of exploration is determined by the site condition and the result of the first few borings. The possible presence of weak zones in the immediate vicinity of the site should not be overlooked.

Subsurface Exploration Record and Reports

Subsurface explorations, without adequate recording of the necessary data and identifying and preserving the extracted samples is a complete waste of time and money. It is imperative that the field record of each subsurface exploration, should be a legible, clear, complete, concise and permanent account of the progression of the exploration.

Such a record constitutes the log for that exploration and should be prepared immediately, concurrent with the progression by the investigator. Proper preservation of field logs is very important not only to the design and construction of the structure/project but in reference to other possible projects in the area in the future (Lambe, 1951).

B. Field and Laboratory Testing of Rocks and Soils

In the beginning there was no systematic basis for the planning and execution of the engineering endeavors and it solely depended on the intuition and experience. For several decades the bedrock was considered as ultimate of strength and stability. However, increased foundation loading by larger civil engineering structures and several major disasters have drawn the attention of earth scientists to conditions which, induce instability in the rock and soil foundations, as well as, in the surrounding areas forming hill slopes. Although several structures are directly founded on the rock yet the physical properties and the structural behaviour of the rock mass under the changed environment of induced stress is not properly known. The optimum utilization of rock foundation for economical and rational design of multistoried buildings, bridges and other heavy structures requires the best possible quantitative data concerning the rock and soil characteristics and its proper interpretation and analysis.

Methods of Sampling

To establish engineering properties of foundation rock or soil, adequate tests may be required in disturbed or undisturbed (natural) state. Methods for testing rock or soil samples (Taylor,1960; Murthy, 1984) obtained from test holes are given in table- 4.

Table. 4

Type	Procedure	General uses
1. Highly disturbed Samples	Auger boring, wash boring & percussion drilling.	Shavings or cuttings of soil brought up by auger, soil particles carried by wash (return water) or dust & chips from percussion drill are indication of type of rock and soil encountered.
2. Split spoon	A standard split spoon sampler is about 5 cm (outer dia.) 30-60 cm long tube which splits longitudinally in the middle	1. Taking disturbed samples. 2. Taking samples from hard soils. 3. Taking samples from soft rocks.
3. Thin walled Tubes	16 gauge seamless steel tube commonly 5-7.5 cm dia. preferably pushed by static force instead of driven by hammer.	Taking undisturbed samples from cohesive soils.
4. Core boring	Rotary drills	Rock samples.
5. Hand cut samples	Cut by hand from the side walls of test pit.	Samples are least disturbed not commonly used because of large expenses involved.

Laboratory and field testing of rocks and rock masses

In accordance with the International Society of Rock Mechanics practice the various laboratory and field tests can be categorized as:

Category I: Classification and characterization of Rock Material (Laboratory tests)

1. Density, water content, porosity, absorption.
2. Strength & deformability in uniaxial compression, point load strength.
3. Hardness , abrasiveness.
4. Permeability
5. Swelling and slake durability.
6. Sound velocity
7. Micro-petrographic description.

Rock Mass (Field observations)

8. Joint system, orientation, spacing, openness, roughness, geometry, infilling & alteration.
9. Core recovery, rock quality designation and fracture spacing.
10. Geophysical logging of bore holes.

Category II: Engineering Design tests

(Laboratory tests)

1. Determination of strength envelop (triaxial and uniaxial compression and tensile strength tests.
2. Direct shear tests.
3. Time-dependent and plastic properties.

(In-situ tests)

4. Deformability tests (Plate jack test).
5. Direct shear test.
6. Field permeability test, ground water pressure and flow monitoring water sampling.
7. Rock stress determination (extensometers).
8. Monitoring of rock movements, support pressures, anchor loads, rock noise and vibrations.
9. Uniaxial, biaxial and triaxial compressive strength.
10. Rock anchor testing.

Laboratory and field-testing of soils (Soil Mechanics)

Table-5 : Field tests

Purpose of test	Type of test
1. Compaction control	Moisture, density.
2. Shear strength (soft clays)	Vane test
3. Relative density (granular soils)	Penetration test.
4. Permeability	Pumping test
5. Bearing capacity	CBR plate bearing test
6. Footing piles (vertical load) Batter piles.	Plate bearing load test, lateral load test.

Table- 6 : (Laboratory tests)

Properties of soil	Type of tests
1. Grain size distribution	Mechanical analysis
2. Consistency	Liquid limit, plastic limit, plasticity index.
3. Unit weight	Specific gravity.
4. Moisture	Natural water content, field moisture equiv.
5. Shear strength of cohesive soils & Non-cohesive soils	Unconfined compression test, triaxial shear, direct shear tests.
6. Compressibility	Consolidation test.
7. Permeability	Water permeability test.
8. Compaction characteristics	Standard proctor, Modified proctor test
9. California bearing ratio	CBR test

In the field tests special mention may be made regarding sub-surface soundings and standard penetration tests.

2. **Sub-surface Soundings:** These tests are conducted for exploring the layers of soils with erratic nature (Meyerhof, 1956; Casagrande, 1967). They are also done to make sure that the sub-soil does not contain exceptionally soft spots located between drill holes and to get information on the relative density of soils with little or no cohesion. Sounding method normally consists of driving or pushing a

cone or a pipe of standard section into the soil.

3. **Standard Penetration Test (SPT):** It is widely used to determine the parameters of the soil in-situ. The test is particularly useful in granular deposits, as a correlation has been established between SPT 'N' values and the 0 of the soil.

The test consists of driving a split spoon sampler by 45cm into the ground at a required level in a borehole. A hammer of 65 kg weight falling freely from a height of 75 cm on the drill rod is used to drive the sampler. The number of hammer blows for each 15 cm penetration is recorded. The total number of blows to drive the second and third 15 cm of penetration is called the Standard penetration resistance 'N', which represents the number of blows/30cm of penetration. Normally SPT in a borehole are conducted at every 1.5 to 2 m intervals. The correlation between the R.D. of granular soils and SPT as suggested by Terzaghi & Peck (1960) are given in Table. 7.

Table. 7

Comp-actness	Very loose	Loose	Medium	Dense	Very Dense
Relative density Dr.	0-15%	15-35%	35-65%	65-85%	> 85%
SPT 'N' Values	0-4	4-10	10-30	30-50	>50
0 (angle of internal friction)	< 28°	28-30°	30-36°	36-41°	>42°

Effect of Temperature Variation

In Himalayas, above 2000 m elevation, severe climatic conditions cause periodical or permanent freezing of the ground, i.e., foundation rock or soil, which changes the stress field in the foundation and structure system. This, very often, results in the tilting and horizontal displacement of the buttress construction, heaving, cracking and sinking of the foundation (Mandwal, 1983). Safe design for building and bridges in such areas is, therefore, very necessary.

Under severe cold climatic conditions the water in the pore spaces of rock and soil freezes. As soon as, the atmospheric temperature drops below freezing point the freezing starts from the ground surface and the thickness of the frozen zone goes on increasing downwards as moisture is drawn towards the surface due to capillary attraction and thermo-osmosis. Development of large heaving pressures may be caused due to this non-gravitational moisture migration.

It is well known, that the water freezing at 0°C increases in volume by 9%. The expansion of water during freezing and the steady growth of the ice crystals due to continuous capillary migration of water from free water table to the freezing front causes heaving. The frost heave thrust is not uniform, its value is greatest at the place where the depth is 60-80% of the depth of frost penetration, less at the bottom and least at the top, generally it is between 1 and 3 kg/cm^2.

The irregularity in heaving is the main cause of distress. The second cause is the excessive accumulation of water and the resulting softness of the ground when thawing of ice takes place during summer. The volume changes resulting from the freezing and thawing of clays are sometimes, as high as, 25%. If provisions are not made to account for these volume changes, considerable damage to buildings and bridges can take place. The heaving pressures, when required, can be reduced to certain extent by avoiding excessive growth of frozen zone, increasing external load, lowering the ground water table by well and pumping, reducing the permeability by grouting, extraction of unfrozen soil between structure and freezing front by boring.

Buildings founded on active layers (soil layer which is subject to seasonal volume change).of permafrost zone invariably suffer heavy damage because of the heat flowing from the building into the permafrost, gets de-freezed (thawed) and loose its supporting capacity. Although freezing increases the mechanical strength of the soil, but the ice lens formation also results in frost heave thrust during freezing period and later in decreased load bearing capacity and uneven settlement in the thawing period. Structures are therefore, founded on eternally frozen ground which, is not subject to volume change so long as it remains frozen.

Various methods are used for stabilization of soil. The buildings are constructed on footings foundation, pile foundation or mat foundation with proper ventilation of the floors.

Seismic Risk Studies

There are several parameters and studies involved in the seismic risk evaluation of any site.

1. Seismic activity of the region
2. Regional geology
3. Cataloguing (preparation) of seismic events.
4. Strain release studies.
5. Earthquake probability studies, return period for magnitude & acceleration.
6. Defining the design earthquake.
7. Seismic coefficient for earthquake resistant design.

The geological evidence of the seismic activity of a region is a valuable tool in the evaluation of seismic risk. It is helpful in estimating the likely magnitude, location and frequency of seismic events. Neo-tectonic activity in the area may be studied. Regional earthquake geology involves the study of tectonic deformation like warping, tilting, faulting etc.

Some of the investigation techniques related to the seismic response of the soils are worth discussing. List of main seismic soil factors with the most suitable tests used in their evaluation are given in Table.8.

Table. 8

Parameters	**Field tests**	**Laboratory tests**
Settlement of dry sands	Penetration resistance	Relative density
Liquefaction	Penetration resistance Groundwater conditions	Relative density Particle size
Dynamic response parameters		

Field and laboratory tests related to the evaluation of the seismic response of soils are listed in Table 9 & 10.

Table.9 (Field tests)

Field determination & tests	**Related to**
Soil distribution & layer depth	Response calculations
Depth to bed rock	Response calculations
Ground water conditions	Response calculations & liquefaction
Penetration resistance	Settlement & liquefaction
Shear wave velocity	Shear modulus
Fundamental period of soil	Response calculations

Table.10 (Laboratory tests)

Particle size distribution	**Liquefaction**
Relative density	Liquefaction & settlement
Cyclic triaxial	Shear modulus & damping
Resonant column	Shear modulus
Unit mass	Response calculations

The fundamental period of soil will generally be between 0.2 and 4.0 seconds, depending on the stiffness and depth of the soils overlying bedrock.

Some of the points, which should always be kept in view while designing a building, one should not forget that the foundation is the most important part of the design.

The multistoried buildings should be designed in such a way so that they may be able to provide sufficient strength in the frame to withstand large earthquakes and their foundation should adequately take due care of possible yielding of foundation soil.

Simplicity and symmetry

Earthquakes repeatedly demonstrate that the simplest structures have the greatest chance of survival. The overall shape should not be too elongated, longer the building in plan, more chances are there of different earthquake movements being applied simultaneously at the two ends of it, a situation which, may produce disastrous results. As such, the investigations should be planned accordingly.

Uniform and continuous distribution of strength

This concept is closely related to that of simplicity and symmetry. The structure will have maximum chances of survival during earthquake if:

i. The load bearing members are uniformly distributed.
ii. The columns and walls are continuous and without offset from roof to foundation.
iii. Columns and beams are coaxial.
iv. Reinforced concrete columns and beams are nearly of the same width.
v. The structure is as continuous (redundant) and monolithic as possible.
vi. No possible principle members change section suddenly.

In qualification of the above recommendation it can be said that, while they are not mandatory, they are well proven and the less they are followed the more vulnerable and expensive the structure will become.

There are three basic types of building foundations viz. Discrete pads, Continuous rafts and Pile foundation.

Continuous rafts or box foundations are good aseismic forms, only requiring adequate depth and stiffness. With the existing know how in the field of earthquake engineering, it is possible to construct tall multistoried buildings safely in severe seismic zones of the country. Due consideration is of course necessary in planning, designing, detailing and construction for which, appropriate investigation and analysis has to be carried out.

Coming to the economics part, in the case of a 16 story block of flats with a reinforced concrete ductile frame it has been estimated, that the cost of incorporating earthquake resistance against collapse, subsequent loss of life and other damages would be about 5 to 6.5% of the capital cost of the building. In a hypothetical study of a railway bridge, up to 18% of the capital cost of the bridge could be spent in preventing the bridge going out of service due to earthquake or weak foundation.

Stability of hill slopes and cut slopes

In case of building and bridges located in hill areas it is not uncommon to see the entire structure sliding or collapsing along with the hill slope. For the safety of the structure various geological factors affecting the stability of the hill slopes in the vicinity of the structure must be known and thoroughly studied by the investigator at the time of site selection (Hoek & Bray, 1972; Anon, 1960).

The relevant factors requiring the attention and proper evaluation are:

i. Geological

ii. Topographical
iii. Hydrological
iv. Rock mass or soil properties.

Such locations where the rocks are dipping towards the free face or valley side specially where, the angle of dip is flatter than the hill slope or adversely oriented discontinuities are present in the rock mass must be looked with suspicion because, they are prone to sliding particularly in the presence of moisture and an impermeable layer underneath the permeable layer. Building or pier sites falling close to the edge of a scarp or at the head of steep slope, active or dead slides, may have a tendency to slide under the load of the building or bridge. The structures founded on the active fault or thrust, are also liable to be disturbed. Buildings or bridge sites located in the snow bound areas must be thoroughly examined/investigated for protection against avalanches. If there is abundant snow, any slope of more than 22° may be subjected to snow slide, causing avalanche and should be avoided. Toe erosion is also responsible for several disasters hence, this aspect must be thoroughly investigated and due care should be taken in designing the foundation.

Conclusion

To sum up, it may be emphasized that the type and nature of the foundation material should be thoroughly investigated prior to finalizing the site and foundation design, by means of surface and sub-surface explorations, field and laboratory tests and the seismic history and status of the area. It should never be an acceptable practice to proceed with the design or construction of even a moderately heavy building or bridge, with out first making adequate geo-technical investigations to have the specific knowledge in regard to the inherent characters of the underlying soil or rock mass with in the zone of influence of stresses to be produced.

The cost of investigation is not much as compared to the savings involved in the safe design and execution of the project. The unforeseen conditions encountered in the foundation, sometimes lead to change the site or design causing considerable delay in the project, thereby, resulting in increasing its cost even by 100%.

The old saying that the foundation soil is always investigated, if not before construction then certainly after a structure gets in to trouble is very true.

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