CONVENTIONAL FOUNDATIONS AND THEIR EARTHQUAKE PROBLEMS

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SYNOPSIS

Present seismic building regulations as used in California include allowances for the effect of a number of variables encountered in building design. However, no variable is included for one of the least understood but one of the most critical factors affecting the design of all structures, the supporting soils and the resulting soil-structure interaction.

This paper includes a review in the fields of normal buildings with shallow foundations on level or sloping sites, and the effect of shallow or deep basements. Also included are observations on retaining and basement walls, mat foundations, underpinning and overturning effects.

A study of normal design procedures for buildings and structures with conventional foundations can focus our attention on the areas where we need more data concerning the soils supporting our buildings. The aim is to generate new ideas and assist in channeling research on the many unknowns in the proper directions.

INTRODUCTION

The problems of conventional foundations, or any other types of foundations, and their relation to earthquakes have been discussed and reviewed periodically since our first earthquake codes in the United States were adopted. However, our current codes include no constructive detailed requirements. Only some general requirements are stated.

The present "Uniform Building Code" is the most widely used seismic code in the United States, either directly by adoption or incorporated in other codes with or without minor modifications. The Uniform Seismic Code presently in use was developed originally between the years 1957 and 1960 by the Seismology Committee of the Structural Engineers Association of California, with subsequent modifications as studies have been completed by committees of the Structural Engineers Association. The latest was published in 1967. Upon reading this code, and even the commentary published with it, very little was actually included regarding effects of variable foundation conditions. Some excerpts from the commentary published with the 1960 code seem appropriate to restate:[1]

"For the present, no variation in base shear coefficients are recommended, nor specified, for differing soil conditions. The following observations have been made:

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"1. The type of structure which is to be built on any given soil condition must be given due consideration as it is evident from observations in past earthquakes that softer soils have created less damaging conditions to certain types of structures than firm cemented gravel or rock foundations. Editorially, the converse is probably the prevalent observation: That certain other types (so-called "Class C" buildings) have fared poorly on softer soils. This has influenced the usual requirement of higher coefficients on poor soils in the past. Here is a specific case where judgment, with an understanding of the dynamic influences of the supporting soils, must be applied to an earthquake resistant structure. As further data on ground motion are obtained it is likely that more refined analyses of response of structures to anticipated ground motion may be justified. These analyses should be encouraged and permitted under administration of the SEAOC code. (Structural Engineers Association of California).

"2. A table of somewhat arbitrary but conservative overloads might properly be included in a code for variable types of soils. Greater increase would be permitted only after adequate foundation investigations were made. Some soils are actually weaker, in a sense, under short term dynamic loading than under long term static loading, while the converse is true in other soils. Loose sands are in the former category, cohesive soils in the latter.

"3. Buildings on light soils should have a reasonably rigid base, with embedment well below grade.

"4. The validity of assuming any horizontal pressures of the ground to resist seismic loading should be carefully evaluated, particularly in view of the possibility of adjoining excavations. Frequently, lateral ground resistance is available only after considerable movement takes place.

"Overturning effects must be carried into the foundations and a careful analysis of permissible overloads for combined effects of vertical and lateral loads should be made as part of the foundation investigation. The problem is to provide safety for the short-time loading during an earthquake (or wind) without imposing such restrictions as to create wide disparity in foundation deflections under normal loading. This disparity could create restraints more damaging to the structure than what might occur in an earthquake under highly increased soil pressure. The advice of a soils or foundation engineer is recommended." (End of quote).

A review of the 1967 Commentary published with the 1967 edition of the Recommended Lateral Force Requirements indicates there is little change in the original concepts of the 1960 version. To quote a portion of the 1967 Commentary:

"E. Effect of Foundations on Base Shear. For the present, no variations in base shear coefficients for differing soil conditions are specified. The basic reasons for this are:

"1. The lack of strong motion records for the widely varying soil conditions that the code applies to.

"2. The complex interrelationship between the periods of vibration of the structure and the vibrational characteristics of different soil conditions.

"3. The uncertainty in the effect of feedback of energy from the structure into the soil in structural response.

"4. The difficulty in assessing simple soil parameters to define the dynamic characteristics of different soil conditions." (End of quote).

In addition, the Commentary adds some further generalizations and refinements. It also again emphasizes that the advice of a soils or foundation engineer is recommended.[1]

Since 1960, most studies by engineers in the United States regarding revisions to the Uniform Seismic Code have centered around other and seemingly more urgent problems such as "ductile frames". Foundations still haven't received the necessary study or priority from the standpoint of codification. From available literature, and data prepared by other engineers and seismologists, it is apparent there is a great deal of research being carried on at the present time. The problem at this point appears to be to assimilate the data and put it into usable code form for day-to-day use.

A review of some previous code requirements relative to variable foundation conditions can prove informational, and possibly helpful. None of the present codes in the United States, to my knowledge, makes any distinction *between seismic factors for different soil conditions. This has not always* been the case. For example, Appendix "A", the building regulations of the Division of Architecture of the State of California in early editions, gave base shear factors varying from .06 to .10 for DL + LL for different soil bearing values. In fact, the 1937 edition made a further distinction relative to soil values and base shear coefficients between "buildings three stories or less in height and buildings without a moment resisting frame, as compared with buildings more than three stories in height with a complete moment resisting frame." Also, present codes of many other countries use varying base shear factors for different soil conditions. The general pattern followed in most codes of other countries results in higher base shear factors as the soils fall into the softer categories.

My discussion will attempt to review some of the common day-to-day practices in engineering offices, pose some questions and dilemmas which we constantly face, and review what we know and don't know. Some suggestions will also be included.

WHAT DO WE KNOW?

Look at the problems of seismic design through the eyes of a practicing engineer. What do we know?

1. We know when an earthquake occurs there is some type of ground motion. This motion varies, depending on many factors such as intensity of earthquake, subsurface conditions, seismicity of site, etc. It certainly depends on the type or types of material on which the footings bear. These motions are undoubtedly erratic and random in nature and of different frequencies, although the motions transmitted through a certain type of soil or

system of soil layers will have some specific dynamic properties and will probably arrive at the building foundation reflecting the specific dynamic properties of those soil layers.[3] Because of the complexity, normal design methods are based upon simplified assumptions. This is a practical approach and is probably acceptable for the present state of knowledge and construction needs.[4]

2. We know that by some means this ground movement is translated into the structure under consideration. One category of loads, the lateral forces, are probably induced by friction at the plane of interaction between soil and footing, by passive earth pressure between soil and footings, grade beams or walls, or by some other means.

3. We know that there is a second category of loads consisting of vertical loading imposed by the structure on the foundations. These can include the effects of vertical acceleration and the tendency to overturn due to the influence of the assumed lateral force. We also know that the effects of these loadings can sometimes create difficult problems, particularly on highly loaded shear walls with large height-to-width ratios. They can also create problems on high, narrow structures.

4. We know that the magnitude of the loads which we must design the structure to resist depends on many factors other than magnitude of the earthquake. One of the greatest variables is the soil supporting the structure. However, many present building codes in seismically active areas specify some static lateral force factor which is intended to result in an acceptable degree of safety for the total structure, regardless of soil conditions.

5. We know that normally no attempt is made to design for the dynamic interaction of the structure and the ground at the present time. This interaction includes the temporary deflections in the ground which absorb some of the energy transmitted to the structure by the earthquake. Also, it is customary to make no attempt to analyze the inter-related effects of the local period of the ground and the structure, and the effects of this interaction on the deformations of the structural elements.[4]

6. We know that most present design criteria have been developed based on satisfactory or unsatisfactory behavior of structures and foundations as observed in prior earthquakes. By studying these observations in relation to the soil and structural conditions, deductions have been made concerning the factors which enabled certain foundations to behave satisfactorily whereas others suffered varying degrees of damage.[4] [5]

7. We know we don't know very much about these problems or the solutions, and we cannot arrive at satisfactory solutions until we more fully understand the problems.

NORMAL PROCEDURES

In the following discussion I will attempt to outline some of the steps we take on normal projects and how we analyze the problems and arrive at the solutions on a day-to-day basis:

1. Codes:

One thing we do on a daily basis, whether we like to admit it or not, is to follow some governing code, assuming and hoping we are designing a safe structure. This is particularly true on the so-called Type III low buildings, usually with limited construction budgets. It is seldom that any engineer designs to a greater seismic factor than the code requires, but he may in some cases provide added *safety factors in certain building elements*. Yet we know that all types of buildings or structures, even if identical in design, materials and construction, do not react the same on different types of soil.

2. Foundation Investigations:

One of our first steps as soon as a project and site are defined (and sometimes before the site is settled, as an aid in locating structures and other facilities) is to call in a competent foundation engineer for a complete subsurface investigation and report. We try to work very closely with the foundation engineer. We believe the best solution is a joint effort between the structural engineer and the foundation engineer. We do not normally have a separate geological study made except on unique or important structures, or unless some special problem is indicated, such as fault zones, ground rupture, landslides, acute vibration problems, etc. Perhaps they are more important than we sometimes realize and we should have geological studies made more often.

3. Conventional Spread Footings:

Based on factors we assume we know, and the tools and data with which we have to work, we can then explore how normal buildings and structures will react with relation to surface penetration by the structure, slope of site and proximity of adjacent structures.

a. First consider a normal building without basement on a *flat site*. The problems here are probably as simple as they can be for any structure. Having selected the applicable seismic factor, we use the predetermined friction factor to transfer lateral motion from soil to structure. Unless a space frame is used, the resistance will be provided by the friction between soil and footings of the exterior and/or other shear walls. The floor slab or added struts may be utilized also to resist the load or spread the load to other footings if properly interconnected. If loads and resistance are still out of balance, other means such as passive earth pressure against subsurface elements must be provided.

The coefficient of friction between soil and concrete is usually assumed from 0.4 to 0.6 of dead load. Some foundation engineers do not recommend combining the friction and passive earth values. Others permit some combination, but generally limit the combination to 100% of one value plus 50% of the other value.

Overturning and resulting excessive soil pressures due to short time loads may be factors needing consideration in special cases for simple buildings. It is axiomatic that spread footings should not be placed on weak compressible soils where critical differential settlement may occur, or when the soil has a tendency to liquefy.

Plate #1 shows a cross section of a simple building falling in the category described.

b. For a similar building with one or more basements, an additional problem presents itself. Where is the base of the building to determine the base shear coefficient, and what is the effect of setbacks? These are problems mentioned here only because the soil interaction is indirectly affected by them. Plate #2 shows two conditions, grade at top of base structure and grade below top of base structure. Aside from these special problems the nature of the solution is generally as described above. Added factors to be considered are passive pressures on the basement walls, which will be discussed later.

c. Related problems can arise on a building located on sloping ground as shown on Plate #3. Undoubtedly there is a different reaction depending on movement or forces to the right or to the left. The base would probably be considered at the lower level. Most of the loads will be transferred through friction, at least in one transverse direction.

d. Still another commonly encountered condition is illustrated on Plate #4. This indicates a long structure with foundations located partially on natural ground and partially on controlled engineered fill. Here the problems expand to include the interaction relation and variable accelerations created between footings on different types of soil created by site conditions.

4. Mats:(5)

A special category of spread footings is one commonly called a mat foundation. A well-designed mat can often be used to spread the loads and minimize differential settlements where individual or continuous wall spread footings would not be applicable. Mats should not be placed on material that can liquefy or is subject to high loss of strength during short time loading, such as seismic action.

The superstructure analysis usually results in a trapezoidal load distribution on the mat foundation, with higher edge pressures occurring during the seismic loading. It is customary in these circumstances to restrict the short time edge pressure to an amount not more than one-third greater than the permissible static bearing pressure beneath the mat, but precautions on soil bearing increases should be carefully evaluated.

5. Basement and Retaining Walls:(4) (5)

Normally, basement and retaining walls are designed for some equivalent hydrostatic pressure, generally based on earth-pressure theory. Inasmuch as the movement of the ground during an earthquake transmits forces into the structure through its buried elements, it would appear reasonable to believe that relatively large additional lateral pressures must be exerted on the basement walls and buried portions of a structure during an earthquake. Checking with some of my foundation engineer friends indicates no evidence of basement wall failures from this source. It is possible that the normal designs of such walls provide sufficiently high factors of safety that high transient stresses can occur without damaging the walls, or that lateral pressures do not greatly exceed the static pressures. We have analyzed some fairly major structures with basements to determine the lateral earth pressure assuming full passive (or active) application. Without considering friction, pressures in excess of 800 pounds per square foot were calculated. It is obvious that if this magnitude of pressure existed, failure would result.

In the case of retaining walls of cantilever or buttress design, documentary evidence indicates there have been numerous observations indicating the occurrence of some lateral deflection or tilting during earthquakes. However, evidence again indicates the number of serious failures of these walls in earthquakes is remarkably small. These observations suggest that, even though temporary lateral stresses appreciably higher than normal are developed during an earthquake, the duration of the stresses is usually so short that only relatively small permanent deflections are created.

In our own practice we seldom include any effect of dynamic or added lateral loads due to seismic effects, either for basement walls or retaining walls. However, studying results of the Niigata earthquake of 1964 as reported by the Japan National Committee on Earthquake Engineering, it appears some side effects such as differential settlement and liquefication could have a material effect under certain conditions.(6)

6. Overturning and Related Problems:

One of the most critical and probably least understood daily problems confronting the engineer relates to overturning and its various counterparts such as differential settlements and compressible soils. This is also an area where an adequate foundation investigation and evaluation are of extreme importance. Overturning is usually not critical for entire structures unless of a special configuration such as towers and stacks, or tall, narrow structures. However, it can be a problem for individual footings, mat foundations, and particularly for shear walls.

Most codes permit bearing increases on footings of approximately one-third when lateral forces are combined with static loads. We find most foundation engineers recommend the same. For most soil conditions the safety factors for static loadings will safely permit such increases when combined with the transient earthquake loads. The important factor here appears to lie in the ability of the person making the evaluation to determine which soils are likely to lose strength under seismic vibratory loadings. In such cases an increase may be unwarranted, and even a decrease may be necessary.

Returning again to the comments in the SEAOC 1960 Commentary for the Uniform Seismic Code, one important problem raised by these considerations is to provide safety for the short time load application during an earthquake, without imposing restrictions on the footing bearing pressures that may result in critical differential settlements under normal gravity loads. Severe differential deflections under normal loading conditions can create distortions and resultant strains which can be as damaging to the structure as those which can occur during an earthquake due to higher transient soil pressures.(1)

Each individual problem should be resolved based on its own individual characteristics. Our general practice, as previously indicated, is to work jointly with the foundation engineer for the final solution.

SPECIAL PROBLEMS

Special problems often present themselves in the design of structures. Although we may not know the answers, if we can recognize there is a problem it at least can help in the ultimate solution. Some of the special problems referred to include the following:

1. Structures supported on highly variable soil, possibly ranging from very soft material to very hard rock and including the intermediate ranges of controlled fill. Generally the best answer is to avoid such conditions if possible. If not, building separations may be appropriate.

2. Elevated tanks and towers and tall stacks. These have had considerable study and I leave recommended solutions, even on conventional footings, to the "experts".

3. Introduction of deep basements adjacent to an existing structure will probably require some type of underpinning, such as:

a. Conventional underpinning in progressive stages.

b. Some system of protective or supporting piling.

c. Soil stabilization where applicable, by such means as soil cement, chemical injections, etc.

At least two problems are evident. Does this affect the structure already designed and built? Does underpinning change the character of the response and interaction between soil and structure? What is the effect on the new structure? Should there be a complete separation below grade under certain conditions even though difficult to accomplish? The effects of adjacent excavations or slopes without adding structures can fall within the same category. Consideration should always be given to the effects of these conditions relative to lateral stability. Too often these factors may be ignored.

4. In an abstract sense, there are two somewhat special problems, particularly for the practicing engineer. These problems may not seem to have a place in this discussion, but I believe they do since they play a vital role in our lives. Economically, as practicing engineers, we must consider these factors or we will cease to be practicing engineers:

a. The first problem is a tendency toward complexity of building codes. If true, and they do become too complicated, we have only ourselves to blame. However, I believe that by some legal means we may have to leave more to the ingenuity and judgment of the engineer rather than attempt to write all possible contingencies in the code.

b. The second problem is keeping informed on latest research and development. Most engineers simply do not have time to read, let alone digest, the tremendous volume of technical data that passes our desks on a day-to-day basis. Is there some means we can use to separate the grain from the chaff, to better utilize what time we have available? Reading data hurriedly can sometimes be disastrous if proper background material is not known. I usually look at the conclusions first, and try to benefit from them. I do not want to be presumptuous, but I believe our educators and researchers keep the communication media with engineers on too high an "intellectual" plane for the "average" practicing engineer to always fully understand and grasp the important conclusions which should be available from papers and reports. On the other hand, maybe we as engineers fail to keep ourselves adequately informed and current with developments to properly serve our profession and clients.

NEEDED DATA AND RESEARCH

One method of determining needed data and research is to review what we don't know. Stated in general terms, we don't know enough about soil characteristics or the interaction between soils and structures during seismic disturbances. To be more specific, following are some observations and questions which might assist in generating needed data:

1. I am advised that there are at present no well established tests or analytical criteria which enable a definite determination to be made as to whether a certain soil material will or will not lose its strength, or to what degree its strength would be impaired, under specific conditions of moisture, confinement, and intensity and duration of stress.(4) Reliable, practical test methods are needed to make these determinations. However, I understand tentative recommendations have been made on determination criteria for liquefication.

2. The interaction of footing and soil, particularly under spread footings, must be generated by movement in the soil. An interesting observation relates to the plane of movement and possible "slippage" or relative movement on this plane. Does some relative movement decrease the load induced in the structure? If so, is it advantageous to have a small amount of movement? Could this be at least a partial explanation of the different response of similar buildings on similar soils? Quantitative data measurements could be beneficial in this evaluation.

3. No reliable data are presently available concerning stresses and deflections which are imposed upon retaining walls and particularly basement walls of buildings during earthquakes. There seems to be a definite need to develop more reliable quantitative data which could be incorporated into the design of basement walls and other retaining structures in order to produce a desirable balance of safety and economy for the behavior of such structures during severe earthquakes. In addition, procedures are needed to provide means for assessing the possible extent of wall movements during earthquakes.(4) (5) Of particular concern would be the relationship of movement and resulting load in the more flexible basements (few shear walls and long, less rigid diaphragms) as used in ductile moment resisting space frames as compared with very rigid basement structures with short rigid diaphragms and closely spaced shear walls. One theory holds that walls of

basements, particularly deep basements, move with the period of the ground which would partially explain lack of build-up of excessive stresses. Does the rigid basement structure have a closer correlation of movement with the ground than the more flexible type, or is there any appreciable difference? This could have a definite effect on dynamic build-up of pressures.

4. Is there some method through building and ground instrumentation that measurements can be made and relationships correlated to explain apparent inconsistencies in damage to buildings of similar construction on similar soils in the same general vicinity (similar conditions of seismicity)? The National Academy of Engineering Committee on Earthquake Engineering Research Report (U.S.A.) cites examples by observation, including the 1906 San Francisco earthquake, the 1933 Long Beach earthquake and the 1964 Anchorage earthquake, where numerous buildings were severely damaged, while those nearby survived. The differences are not presently explainable.(4) Reports on the Caracas earthquake of 1967 which I have heard and read, indicate the same inconsistencies occurred.

Such observational data emphasize the need for engineering research studies which will enable engineers to attain a better understanding of the interaction of the ground and the structures during an earthquake. Through such studies, it seems reasonable to believe that the apparently inconsistent and conflicting behaviors which have been observed in the past may be explained.(4)

5. To review some more detailed items and practical considerations, the following seem worthy of some thought:

a. What is the effect, if any, of vertical acceleration on friction values or passive earth pressures?

b. The effectiveness of foundation ties, either as struts or through slabs on grade, should be more effectively determined with relation to soil types. For sites with weak soils, and even in the better soils, I believe they can often be of great benefit.

c. Is there a variation in interaction within the length or width of a structure? On long structures with variable soil conditions, variations would seem logical. Certainly, a long building partially on cut and partially on fill, can have variations in interaction develop within its length. Such a condition was illustrated on Plate #4.

Probably most, if not all of these questions can be satisfactorily answered for each individual project, once the basic methods of tests for evaluating sites and soils are perfected.

6. Ultimately, the data needed is material in a code form the practicing engineer can use. This may lead to variable shears based on different soil and subsurface classifications, variations due to rigidity of structure (although this is already partially accounted for in codes), or some other approaches not yet seriously considered.

CLOSING COMMENTS

1. At the time the 1960 Uniform Seismic Code was written, it was concluded that the SEAOC committee could not develop results that could be codified. The study group further concluded that due to the fact that earthquakes vary and that each earthquake will further vary at different site locations, more records were needed before any general conclusions could be drawn. Rather, it was stressed that each project be individually studied with a soils consultant to determine the type of foundation best suited.[1] [7] Seven years later, the same general conclusions were presented in the 1967 edition. These conclusions may be entirely correct, but I question if they are necessary on a continuing basis.

It seems an appropos time for the Structural Engineers to concentrate on a comprehensive study through their Seismolcgy and Code Committees, leading to desirable code revisions, covering the effects of subsurface soils on the supported structures. Where data are not now available to properly evaluate the effects, they can and should encourage a cooperative and accelerated research program to develop the desired data. I believe this will be one of the most desirable and productive means to resolve the unknowns and produce a practical, workable approach to a very complex problem.

2. It appears to me, one logical step to help bridge the gap between research and its practical applications, is a more active participation by the foundation engineers. They can provide valuable assistance in translating the available test data into useful code form and can also assist in steering research into the proper channels. We now have several outstanding foundation engineers involved in the activities of EERI.

3. Normally, major sophisticated buildings receive much more attention during the design and construction phases than the more common Type III commercial and industrial buildings, due probably to their relative individual importance and the dollar value of each project.

One suggestion to expedite development of meaningful criteria could be to concentrate first on low rise buildings of the rigid or semi-rigid type. This is the area where most of the construction dollars are invested and where the least design effort is usually available or used. I believe we may best serve the public by this approach. A frontal approach on the overall problem may tend to overwhelm us. Perhaps an approach by stages, can be beneficial and help to expedite the final solution. Are we tending to concentrate too heavily on the more glamorous high rise field of structures because of their appeal?

4. Since we are dealing with a material composed entirely of variables about which we have limited knowledge, do the best we can with the knowledge we have and hope the next major earthquake cooperates with us.

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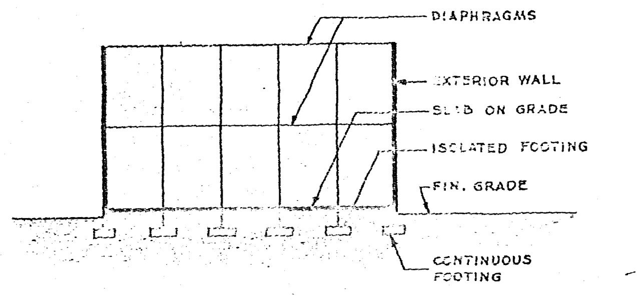

PLATE # 1

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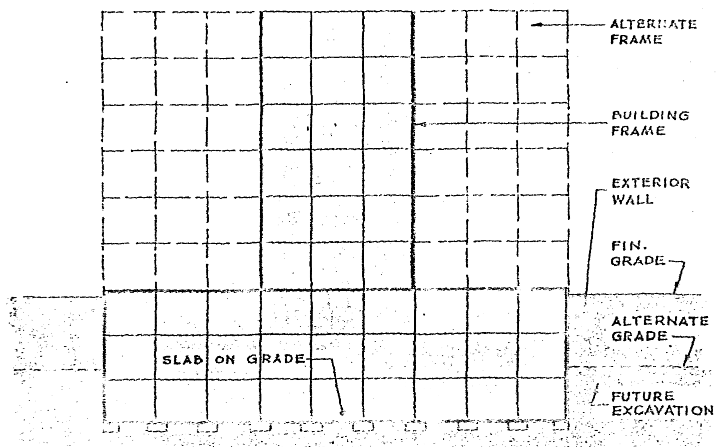

PLATE # 2

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PLATE # 3

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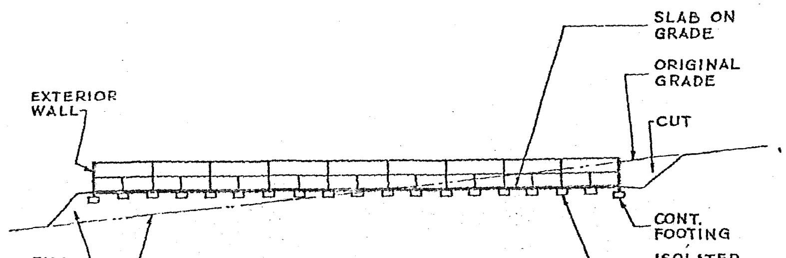

SECTION SHOWING STRUCTURE ON CUT AND FILL

PLATE # 4

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