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LAWRENCE LIVERMORE LABORATORY

University of California/Livermore, California

SEISMIC PROTECTION OF BURIED STRUCTURES

A. Blake

September 15, 1972

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Seismic Protection of Buried Structures

NAME

A. Blake

Asilomar Conference 1972

DATE September 1972

This note is based on several informal discussions and technical presentations attended at Asilomar, September 5-10, 1972 and sponsored by the Engineering Foundation. Since no formal proceedings and printed records are anticipated, the note attempts to summarize those findings which may relate directly to special projects in earthquake design and analysis under consideration at the Nuclear Test Engineering Division.

The theme of the conference was "Earthquake Protection of Underground Utility Structures." The information presented indicates clearly that the research on underground seismic effects is long overdue because the major efforts have always been directed towards the analysis, test and design of above-ground structures. Recently the American Society of Civil Engineers established a Research Council on Underground Construction to create and introduce practice of new technology and methods of construction. The overall research plan calls for defining criteria, justification for the use of resources, developing detailed research programs and methods of implementation to mention a few. However only very limited funds were allocated to this end by the Engineering Foundation and the National Science Foundation.

In terms of the scientific efforts at various major universities the situation is changing although no new breakthroughs appear to be forthcoming. The experts in the field of seismic design of underground, buried structures seem to be rather few and far between. However the authorities who enjoy national recognition are going to make special efforts during the forthcoming national and international conferences to assure their share of support from the utility industries and government agencies.

The opinions of the utility industries on the subject of seismic protection of underground structures are as yet generally mixed and in some instances definitely against the undergrounding. This kind of a reaction should be expected and one has to look first for changes in the attitude of the general public and the government agencies in this particular area of underground construction. There are signs however that the general situation is changing fairly rapidly and we can expect more utilization of underground space, requiring improvements in the methods of seismic design and the corresponding predictions of reliability.

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When this occurs, considerable demand for technological advances in this area will develop. It seems that a portion of our own Laboratory effort should be directed to problem solution in a non-weapon area of national need. Based on my own observations at the Asilomar Conference I feel that we may have a competitive technical edge in the area of facilities and general experience which can be adapted to seismic work. Unfortunately our capability in this area is unknown to utility industries, universities and even one of the government agencies with which we have rather close ties.

Before proceeding with various detailed observations gathered during the Asilomar meeting, it may be interesting to summarize the present position of Bureau of Reclamation on the general subject of reliability of underground utilities, as described to us by the Commissioner:

- Relative intensity of vibration below ground is expected to be less severe than that on the surface.
- Design of structures to accomodate ground displacements is generally not feasible.
- The system should be placed just below the surface when close to active faults.
- Where displacements are not anticipated, placement of utilities at greater depth is recommended.
- There are virtually no methods for designing safe buried pipes crossing active faults.

One of the first items discussed emphasized the distinction between the usual concept of ground motion described in geological terms and ground failure as a design parameter. It was pointed out that soil conditions affected the extent of ground motion and for this reason underground motion could be expected to be less than that on the surface. The ground failure included the considerations of faulting and local tensions due to the ground spreading during an earthquake. Limited underground motion data available for design purposes was obtained by the Japanese investigators. The study indicated that the motion intensity decreased with depth of burial, with some limited exceptions.

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The problem was described as highly frequency dependent. The Japanese measurements of motion intensity were made in Alluvium and the multiple reflection theory was used to predict underground motion utilizing surface motion and sonic velocities of soil as input. The natural frequency in Alluvium was about 2 to 4 c/s, with the total theoretical range studied between zero and 10 c/s. The observed spectral intensity was found to be much more sensitive in Alluvium than in the rock, making Japanese findings similar to those recorded at NTS. As far as the general design rule for buried pipes was concerned, the flexible pipe or electrical conduit was normally assumed to be moving with the ground. Under such conditions the stress could be calculated from the assumed shape of the deflection line. For relatively rigid conduits and pipes, load distribution and knowledge of support would be required before attempting any closed form of finite element calculations.

The problem of soil failure and the response of cohesionless soils was studied in the Laboratory during the past ten years under the sponsorship of NSF. The failure under cycling conditions was induced by means of a sinusoidal motion and was correlated with the cycles to failure and deflection. Higher confining pressures were found to be generally associated with the higher numbers of cycles to failure. As the loading on soil increased the nonlinear behavior was reached fast. Liquefaction mechanism was observed on a typical cohesionless soil utilizing cycling loading. The maximum ground acceleration at which liquefaction occurred was established as 0.05 to 0.15 g. The above tests were run by a local consulting firm and further details on this subject may be obtainable.

The subject of relatively large openings in rock (span 50 feet and more) was discussed briefly on the assumption that static, elastic analysis was applicable. The measurements of particle velocity on the wall of a large cavity during blasting was indicated to be 5 to 7 inches per second. Some of the cavities on which the measurements were taken were 60x150 feet. The design was usually based on gravity loads and test data on elastic displacements, obtained by mechanical extensometers. When excavating roof of the cavity, the pressure required by the support structure was normally taken to be:

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Pressure = (Height of Loose Rock X Unit Weight) - Cohesion Strength

Several useful rules of thumb for the design of rock cavities may be summarized as follows:

- For a conical shape of roof excavation with θ equal to half cone angle, the stability decreases with an increase in θ .
- Bolt length is usually equal to $1/4$ and $1/3$ span of the cavity.
- Rock bolts are normally pretensioned to about $2/3$ of yield of bolt material.
- The depth of layer of loose rock in the cavity walls was observed to be equal to about 5 to 10 percent of the cavity height.
- Dynamic analysis is considered to be applicable when rise time of the stress wave is less than half the transient time across cavity.

Electrical conduits buried underground received due attention since, structurally, they fall into the broad category of pipelines when subjected to earthquake environment. The consensus of the opinion of the manufacturers of electric equipment in general was that no information was available on underground forces and seismic design in this particular area. While rigid body and spring methods are used in the dynamic analysis of electrical components and systems no specific methods are available for flexible and rigid conduits. Because of the differential seismic motion always present on such structures, the cables may be subject to shear, compression or buckling failure. Special attention should be paid to hard points at various cable attachments and to pressurized pipes used for cable containment.

In the area of water supply there may be pipes, ducts and tunnels of circular or rectangular cross-section, often required to cross active seismic regions and faults in particular. In many cases after seismic activity various deflections and different modes of failure can be observed. Unfortunately it is not feasible to make reliable calculations based on the observed deflections alone, although some attempts of such analysis are made. In tunnels high vertical loads may be present, inducing appreciable lateral forces which lead to wall

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bulging. To interpret, say, the deflection due to bulging it may be necessary to know the stress distribution around the tunnel periphery as well as detailed mechanical properties of the surrounding material with their non linear effects. Experience with earthquake response, however, accumulated generally useful information on the behavior of reservoir walls, water tunnels and large pipes under seismic input. It was observed for instance that the intensity of horizontal shaking on a reservoir wall was greater than that in the vertical plane, resulting in principal shear failure of the wall. Large pipes, those in the range of 6 to 8 feet in diameter, were damaged at joints due to the appreciable horizontal displacement. The horizontal deflections in various earthquakes were reported to be in the range of 1 to 12 inches, with lateral accelerations equal to about 0.3 to 0.4 g. Smaller pipes such as 16 inch oil or gas lines failed mainly at the joints, and the fractures were reported to be of a compressive nature.

The theoretical model postulated for buried pipes by Newmark is based on the premise that the relative strain between the two points should be considered to be the most important parameter. This model was proposed several years ago and no new developments appeared to be available at the conference. The model develops relative displacement between the two points using standard wave propagation equations, assuming evidently no interaction parameters between the pipe and the soil. It appears therefore that the pipe in such a model must move with the soil, regardless of its flexibility and regardless of any frictional and flow characteristics of the soil. Although such a model has merits when one considers a flexible conduit, the questions may arise when the pipe is more rigid and the soil less rigid, including the extreme conditions of liquefaction. The difference between the Newmark model and NTED model of modified lateral pressure may probably be explained in terms of relative rigidity of pipe and soil. The same concept of relative rigidity enters the considerations of mitigation analysis which may be described as the method of controlling the trench geometry, frictional interaction between the pipe and the backfill, as well as backfill material properties. Such a control may result in cushioning the effect of seismic forces or allowing additional room for the pipe to move above ground in order to escape seismic pressure of soil provided the pipeline is buried sufficiently close to the ground surface.

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The concept of possible control of frictional resistance between the pipe and the backfill material referred to during the conference appears to be essentially the same as that proposed in our NSF proposal.

It may be of interest to note that while serious efforts are being made on our part to secure the support of NSF for seismic work, the AEC already supports various organizations in similar studies with special reference to siting and design of nuclear power plants. The requirements for site evaluation state that no surface faulting must occur during service life. Because of the general lack of information on seismic intensity and soil properties, elastic analysis and conservative response spectra are employed. Amongst the material properties required were such as damping factors of concrete, dynamic shear modulus of soil in situ, and liquefaction characteristics. Special studies underway as part of the general seismic research program included soil-structure interaction, earthquake simulation, ground amplification, non-linear effects of soil column, USGS mapping of seismic activity, and the relation between the overburden pressure and cycling loading.

Sizeable portion of the meeting was devoted to the discussion of feasibility, design and containment features of undergrounding nuclear power plants. Studies made in industry show that undergrounding does not in general save the overall volume. For a typical 1100 MW plant the minimum space required for underground placement would be a cylindrical cavity of 120 feet in diameter and 200 feet in height. The containment lining would consist of a steel liner and a concrete wall. The design criteria should specify no faults or shear-zones in the plant vicinity and would require predictable soil formations. Because of the size of the cavity differential seismic forces on the containment system should be expected. Cooling water system failure can not be tolerated and the relevant design criteria should be as stringent as those for the reactor itself.

One of the major problems facing the industry providing nuclear power plant components is the degree of conservatism built-in into the design by the accumulation and pyramiding of safety factors. Since the damage to buildings and machinery sustained by earthquake is difficult to correlate with seismic intensity there is a natural shift in the specifications to higher "g" values.

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However the AEC spectrum data applicable to design is considered by some of the manufacturers as not unduly conservative. The difficulty lies in the fact that while the buildings may have one dominant mode, the equipment protected by this building could have a multimode response. The three dimensional dynamic analysis as reported by the industry includes models of reactor building, floor response, multiple excitation, hydrodynamic mass effects and structural damping. There are numerous uncertainties in the analysis caused by the stiffness and mass distribution, natural period of the supporting soil, non-linear effects, time history and variations in physical properties as well as boundary conditions. In the absence of better data synthetic time history is usually taken in the calculations. To assure certain degree of conservatism, lower damping values are often specified while the design to a spectrum envelope, normally preferred by the utility industry, introduces another conservative factor.

The construction industry appears to be generally of the opinion that underground placement of nuclear power plants may be feasible. The depth of emplacement was quoted as 200 to 300 feet, with certain geological limitations on maximum roof spans and wall stability. Transportation during the construction process and assembly logistics with special regard to cooling, ventilation, emergency power supply, containment closures and other operational and safety aspects must be expected to increase the total cost of the project compared with that of a conventional nuclear power plant above ground. The probability numbers for the more conventional designs were quoted as follows:

- Pipe Failure 10^{-4}
- Tornado 10^{-4}
- Plane Impact 10^{-6} to 10^{-9}
- Missile Incident 10^{-9}
- Earthquake 10^{-7} to 10^{-8}

The US practical experience and various theoretical studies indicate that containment problems for plant undergrounding have not, as yet, been fully solved in relation to the seismic risk.

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The experience and attitude of European industry, represented by the Norwegian and Swedish participants at the conference, appeared to differ significantly from that of the US. The first test reactor, for instance, was placed underground in Norway. Sweden and Belgium have similar designs completed and containment problems solved. The immediate reasons and advantages for putting nuclear power plants underground in those countries could be summarized as follows:

- Defense Protection
- Metropolitan Siting
- Stable Geology
- Lower Overall Cost

The proposed Swedish reactor will be placed about 150 feet underground in a rock formation. The cavity is rectangular with extensive rock bolting. According to the Norwegian records the cost of rock bolting in such projects would amount to about 10 to 30 percent of the total construction cost. The most important and a rather unique feature of the Swedish project is double-containment concept utilizing circulating water system and double shell design of reinforced concrete type. Only general outline of this concept was given, and no published material was available at the conference. Further information, however, may be available if the idea of an International Committee for Underground Nuclear Power Plants, proposed at Asilomar by the Norwegian representative, becomes a reality.

There was no agreement between the US and foreign participants regarding the cost of underground placement and containment. It seems that the European and our own predictions represented the two extremes, low and high respectively.

Special mention should be made of the Canadian Hydro-Power experience in relation to power undergrounding in general. It appears that security, economic, ecological and right-of-way conditions in urban areas will force generation and distribution of power underground. For instance Montreal alone will need 35 power stations in the near future with no right-of-way available.

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Whether the problem is that with the nuclear or conventional power, including geothermal, high voltage lines are necessary. The industry is particularly sensitive to hardening requirements and restrictive seismic specs for underground placement, because of cost escalation. The industry feels that the following areas of related technology and standards need further work:

- Definition of Seismic Environment by means of response spectra.
- Design and Test Activities should be based on Frequency and Damping tests.
- Better Mathematical Models should be developed for Equipment - Foundation - Soil Interaction.
- Cost/Benefit ratios should be derived on the basis of tests because of poor definition of Seismic Risk.

The conference on seismic protection of structures would not be complete without a brief reference to Trans-Alaskan Pipe. As presently envisaged 48 inches diameter pipe will be placed underground for about half of its total length of 800 miles. Legal procedures and technical considerations involving soil parameters, seismic specifications and the effect of heat transmission on permafrost, are some of the factors affecting the delay. Ecology introduces additional requirements of animal crossings and pipe integrity detection devices. Present design level is defined as 5.5 to 8.5 on the Richter Scale depending on the location, and allowances are made for fault crossing and liquefaction. Trade-off studies continue since some of the authorities feel that above ground pipe may be safer. Although not stated explicitly at the conference, it is likely that Newmark's flexibility method of seismic design was used to calculate 5 foot lateral motion of the Alaskan pipe. The term "flexibility" used in this report refers to the premise that strains and displacements are deemed to be the most important parameters. This approach leads to the design philosophy that all buried pipes should be made flexible and ductile to accomodate deformation, while their joints should be correspondingly stronger.

To test this and other theories of buried pipe response field and Laboratory measurements are required. Such measurements should also provide a sound basis for establishing limits of the design motions and a check on field

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performance, in relation to the properties of backfill material. The concepts of flexible and rigid pipes may be investigated in the same type of experimental rigs.

The attitude of utility industry appeared to be governed mainly by cost and hard facts rather than be any other criterion. For instance high-level representative of PG&E, made a strong and rather dangerous statement that seismic design is not a consideration with large pipes and other utility components, even in the case of life-lines crossing the faults. In quoting various statistics of satisfactory performance of many miles of gas pipes and power plant lines the speaker asserted that in their judgment there is no advantage in going underground on account of earthquake hazards. The same comment was made regarding undergrounding nuclear or conventional power plants. It was interesting to note that such statements have not come out from other industries, such as for instance Southern California Edison Co., which faced some hard facts during the San Fernando and similar events.

In summary, the following conclusions have been made at the conference:

- Earthquake environment presents relatively fewer problems to the plant itself than to its life-lines.
- State-of-the-art knowledge in design is rather elementary but suitable research, codification and coordination are badly needed.
- Static considerations for underground rooms are satisfactory.
- It is not feasible to design piping for fault crossing with present level of knowledge.
- Equipment can be designed for most seismic conditions if factors of safety and acceleration levels are not escalated.
- The majority of pipelines and similar components fail at attachments.
- Any conduit can go underground provided soil conditions are well known.
- Underground nuclear plant should be protected by double containment.

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- Esthetics and environment are strong and sometimes the only reasons for undergrounding.
- If the state-of-the-art knowledge in seismic response of soil masses is not upgraded, future earthfilled dams will not be built.
- Permanent international organization should be formed to coordinate seismic research and design in relation to underground structures.

The above comments represented the views of the majority but not of all the participants at the Asilomar meeting. Conference Chairman was Professor John F. Szablya from the Washington State University.

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