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Differential Settlement of Nuclear Power Plant Foundations

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SYNOPSIS: A rational approach is presented for evaluating differential settlement of structures at nuclear power plants where settlement monitoring and the associated documentation are important. In nuclear plants, allowable differential settlement is governed by the necessity to prevent architectural and structural damage, equipment malfunction, touching of adjacent buildings during an earthquake, and damage to buried utilities. Measurements of actual settlement of the plant should be taken on a regular basis from start of construction and compared with the allowable values. A description is given of methods for calculating allowable values for differential settlements, and a comprehensive program for obtaining actual settlement data at a nuclear site is outlined. The ratio of measured to allowable differential settlement at which remedial action may be required is discussed.

A case history of differential settlements at a nuclear plant is presented. The settlement patterns exhibited by the major structures can be correlated with foundation conditions at the plant site. Measured differential settlements are small, generally less than 0.25 inch, compared with values of allowable differential settlement which are mainly greater than 0.75 inch.

INTRODUCTION

Predicted settlements for structures are required for a number of reasons. Chiefly, the engineer needs assurance that each structure is stable and can function properly within the predicted settlement range for its design life. Since predicted settlement is a function of the foundation configuration, depth, loading and soils, it generally bears little relationship to the allowable settlement, which is a measure of the settlement the structure can tolerate before damage in one form or another is incurred. For safety-related (Category I) structures, allowable and measured settlement should be compared to ascertain what margin of safety exists, and if remedial action is required. Since settlement monitoring of foundations for safety-related structures at nuclear plants is a requirement, then the main task is to be able to compute allowable differential settlements.

This paper attempts to set forth methods and criteria for determining allowable differential settlements at nuclear plants and describes a program for the regular monitoring of settlement markers to obtain actual differential settlement values. A case history is presented.

ALLOWABLE DIFFERENTIAL SETTLEMENT

In nuclear power plants, allowable differential settlement is governed by the necessity

to prevent:

- o Architectural or structural damage or equipment malfunction
- o Adjacent buildings touching during an earthquake
- o Damage to utilities between adjacent buildings and utilities entering buildings from the soil

Architectural or Structural Damage

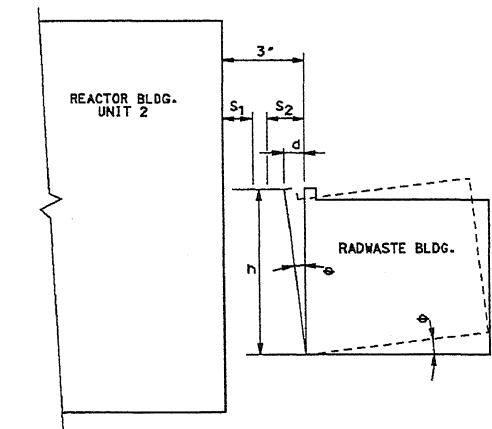
Three situations resulting from differential settlement are considered under this heading, namely: damage to the base or frame of the structure; damage to the cladding or paneling of the structure; and equipment malfunction. Although these three situations are perhaps the most obvious consequences of differential settlement, they are also the most difficult to define in quantitative terms since each building or piece of equipment will respond in a different manner to differential settlement.

For safety-related structures in nuclear plants, the range of tolerable settlements is in line with industry standards for well-engineered structures, i.e., from 0.0015 to 0.003 radians of slope settlement profile (Navfac DM-7.1, 1982); this range covers structural damage and damage to cladding or paneling.

The most sensitive pieces of equipment in a nuclear plant are the reactor pressure vessel and the turbines. Construction tolerances for the pressure vessel can be less than 0.01 inch level difference over the base of the vessel. Turbines have traditionally presented foundation problems as a result of vibrations caused by out-of-balance forces which can develop during operation. Because of the very conservative standards adopted by equipment manufacturers, both the reactor pressure vessel and the turbines should be able to tolerate more differential settlement under operating conditions than is allowed during construction. However, actual values will depend on the equipment used.

Adjacent Buildings Touching

The situation of adjacent buildings touching during an earthquake arises where individual buildings are separated by only inches, as frequently occurs in the plant powerblock (usually incorporating the reactor, control, turbine and radwaste buildings). During an earthquake, the gap between adjacent buildings will widen and narrow as a function of ground movement. If the buildings have previously settled towards each other resulting in a narrowed gap between the top of the buildings, seismic movement may cause the buildings to make contact. The calculation procedure for allowable differential settlement under these conditions is demonstrated on Figure 1. Settlement values are calculated from the angle of rotation required to close one-half of the remaining gap after deducting the seismic movements of the two buildings from the original gap. For each building, allowable slopes along both axes need to be considered.



$$\text{ALLOWABLE SLOPE } \phi = \frac{d}{h} \text{ (FOR SMALL ANGLES)}$$

$$\text{AND } d = \frac{3" - (S_1 + S_2)}{2}$$

WHERE: ϕ = ALLOWABLE SLOPE OF THE BUILDING

d = ALLOWABLE HORIZONTAL COMPONENT OF TILT TOWARDS AN ADJACENT BUILDING

h = HEIGHT OF BUILDING

S_1 = SEISMIC DEFLECTION OF BUILDING AT TOP

S_2 = SEISMIC DEFLECTION OF ADJACENT BUILDING AT SAME ELEVATION

Fig. 1 Determination of Allowable Differential Settlement for the Case of Adjacent Buildings

Allowable settlement values calculated by the above method represent the worst case. In order to touch during an earthquake, differential settlement must be such that the buildings represented in Figure 1 lean towards each other, and both must reach or exceed the allowable tilt simultaneously. Thus, the fact that a building has reached the maximum allowable tilt value is only one necessary condition for touching to occur during an earthquake.

Utilities Damage

Buried piping can range from 8 to 15 percent of the total piping within a nuclear plant and can account for as much as 100,000 linear feet in the bigger units. The piping ranges from large-diameter lengths such as cooling water from the intake structure or steam to the turbines, to small diameter service piping. Since the piping system is basically the sole method of transporting vital materials within the plant, it is essential to ensure that overstressing and possible pipe fracturing does not occur under any circumstances. One potential cause of overstressing of the piping as it enters a structure (referred to as a "penetration") is movement of the structure relative to the penetration. This can take the form of differential settlement between structure and soil in cases of isolated structures, or differential settlement between adjacent structures. The amount of differential settlement each penetration can withstand before the pipe becomes overstressed is calculated from the allowable pipe stress criterion (ASME, 1977):

$$\frac{I M_D}{Z} \leq 3.0 S_C$$

where I = Stress intensification factor
 Z = Pipe section modulus
 M_D = Moment due to building settlement
 S_C = Allowable stress in cold condition

In addition to the pipes themselves, pipe anchors and pipe supports must be considered; the moments and stresses due to building settlement must not exceed the anchor and support design moments and stresses. In many cases, the allowable moment in the anchor or pipe support will be the governing factor.

Once the critical moment is established for the penetration, the amount of building settlement which will produce this moment is computed. The authors' experience is that the bending moment and corresponding level of stress produced by actual differential settlement of nuclear plant structures on properly designed foundations is well below the critical overstressing level for most of the penetrations. Only in isolated cases where the penetration design is tailored to satisfy a particular requirement is overstressing liable to occur. The most feasible approach to calculating allowable building settlement, therefore, is to perform for each penetration simple hand computations of structure movement corresponding to the

critical bending moment; these computations make simplifying assumptions which produce conservative results, i.e., the computations will indicate critical bending moments that are smaller than they would be in reality. Nevertheless, the settlements calculated by the simplified analysis will in most cases be considerably more than the predicted or measured settlement.

For the few cases where the allowable settlements computed by the simplified manual procedure are close to or less than the predicted or, in some cases, the measured structure settlements, more sophisticated analyses are used. These usually take the form of a computer solution, where factors such as anchor rigidity, assumed complete in the simplified procedure, is relaxed to a realistic level to produce a less conservative result. If this sophisticated analysis produces allowable settlements still less than the measured or predicted settlements, a design to include possible remedial measures is the next step. In most cases, a simple modification to the existing design will increase the allowable settlement to a suitable level. Generally, a change of position or detail change in design of an anchor or support will suffice. It should be noted, however, that any change in the design of one part of a piping system will usually entail re-analysis of the whole system affected by the modified part; this may include reanalyzing the system for seismic effects as well as static loading.

In summary, the steps involved in estimating and dealing with the allowable differential structure settlement with respect to each pipe penetration are:

1. Determine the bending moments in pipe, anchors and supports corresponding to allowable stress.
2. Determine which part of the system is critical.
3. Compute the building settlement required to cause critical bending moment using simplified conservative manual procedures.
4. For penetration where settlement established by 3 is too small, employ more sophisticated analyses using less conservative parameters.
5. For penetrations where settlement established by 4 is too small, consider design of remedial measures.

MEASUREMENT OF DIFFERENTIAL SETTLEMENT

Before the start of construction of a nuclear plant, the location of settlement markers should be carefully planned to optimize the amount of information obtained from the measurement program. Markers should be set at the four corners and at the center of each structure. Additional markers may be required where spacing between markers is much more than 100 feet. This placement program will enable detection of overall tilt or

localized sag of the structure; the center marker should also give an indication of the structure rigidity. The markers should be set into the top of the foundation mat as soon as feasible after the mat is poured. Since readings will be taken with conventional surveying equipment, it will be advantageous to make the marker points as accessible as possible. Where the top of the foundation mat becomes difficult to reach after construction of additional floors, e.g., where the foundations are placed in deep excavations, then it may be advisable to transfer the markers to an elevation near ground level. The inaccuracies involved with transfer of the settlement marker, and the differences in settlement measured above the building base compared with at the base, will probably be less than the inaccuracies generated by trying to survey points at inaccessible locations. It is important that any change in marker location or elevation, even if it involves only a slight modification of the marker itself, be fully documented.

Measurement Across Structures

The maximum differential settlement across structures must be measured as a basis of comparison with allowable differential settlement established from structural or architectural damage criteria, equipment malfunction, or adjacent buildings touching during an earthquake. It is important to ascertain the reference dates of the markers, i.e., the date after which differential settlement will affect the performance of the structure or equipment. In other words, the amount of differential movement that has occurred before, say, the turbines are installed, will not affect the turbine operation since the turbines will be leveled during installation. Similarly, any differential movement that occurs before construction of the upper floors of the taller structures will be compensated, since each wall will be plumbed during construction. At the end of construction the gap between the buildings will be as specified, regardless of what movement has already occurred. Thus, differential settlements of the markers will normally be measured with reference to the date of equipment installation or structure completion, not to the date of marker installation.

As discussed previously, a minimum or limiting allowable differential settlement, corresponding to a governing factor such as equipment malfunction, can be calculated for each axis of each building. An additional factor, namely the reference date for measuring this movement must also be considered. For example, the limiting allowable settlement may be 0.5 inch between markers on the north and south ends of the turbine structure, established to prevent the turbine building and adjacent reactor building touching during an earthquake. The differential settlement between north and south ends allowed with respect to satisfactory performance of the turbine is, say, 0.75 inch. However, if the turbines were installed 12 months before completion of the reactor

building, then the reference date for turbine operation criterion would be 12 months earlier than for the building touching factor. It must now be established whether more or less than 0.25 inch of north-south differential settlement occurred within these 12 months. If less occurred, the 0.5 inch allowable to prevent the buildings touching still governs; if more occurred, the allowable settlement of the turbines will now be the governing factor.

Measurement of Penetration Settlement

The maximum differential settlement between structures must be measured as a basis of comparison with allowable differential settlements established for penetrations between structures. The penetration locations will not necessarily be close to the settlement markers. It should be sufficient, however, to assume that the movement of the penetrations will be similar to the movement of the nearest marker. Again, it is critical to establish the completion date of the penetration. It is common to install the penetrations during construction of the basement walls prior to backfilling but to wait until nearer plant completion before anchoring the penetrations. Therefore, completion of penetrations can occur over a wide time range.

For movements of penetrations entering buildings from the soil (as opposed to entering from an adjacent building) it is again sufficient to assume that the movement of each penetration is similar to that of the nearest marker. In these cases, only one marker has to be considered instead of two markers for penetrations between buildings. As with other penetrations, it is essential to establish the date on which the penetrations were completed. For all of the penetrations, the structure settlement in question does not have to be differential across the structure since a uniform settlement will produce the same stresses in the pipes and anchors.

In calculating the allowable differential settlement between penetration and soil, it is usual to assume that the soil adjacent to the building is unaffected by the pipe settlement. In fact, some settlement of the soil in the direction of the pipe settlement will occur, especially the soil immediately adjacent to the building. If no soil settlement is assumed, a larger than actual differential settlement between building and soil will be recorded. It may be possible to detect movement of the soil surface adjacent to the building; however, movements will be so small and the soil surface so irregular that measurement may be precluded. In any case, some allowance should be made for soil settlement in order to reduce the amount of conservatism to realistic levels.

REMEDIAL ACTION

During plant design, if predicted differential movements exceed allowable values, then design modifications are made. If, during plant operation, the ratio of measured to

allowable differential settlement approaches unity, then some form of remedial action must be considered. Considerable judgment is called for in deciding when and what kind of action is necessary. In this respect, the trend of settlement versus time is most important. This trend will be a function of the foundation type and the foundation soil. For shallow foundations in mainly granular soil, most of the settlement will occur during construction; in clays, consolidation settlement may occur steadily for months or years after construction is completed. Thus, in sands, if the ratio of measured to allowable differential settlement is, say 40 percent after construction, it is very possible that the ratio will never reach much more than 50 percent. On the other hand, if the ratio in clays is 40 percent immediately after construction and reaches 60 percent 3 months after construction, serious consideration should be given to making plans for remedial action in the near future. In any case, under all conditions, if the ratio of measured to allowable differential settlement exceeds about 75%, an engineering investigation should be undertaken. Similarly, if the rate of settlement of a marker begins to consistently increase over a period of several months, the cause should be examined. It is important, therefore, that measured settlement data be plotted on a settlement versus time chart as it is accumulated, and that the chart be reviewed regularly by a geotechnical engineer familiar with the foundation design and subsurface conditions to determine if any action is required.

CASE STUDY

To illustrate an example of differential settlement computation and marker measurement, the differential movement history of the foundations of a nuclear power plant in the southeastern portion of the United States will be described and discussed.

The plant has two units, each having a capacity of approximately 600 MW. The settlement study examined the Unit 2 reactor, turbine, control and radwaste buildings in the powerblock area, and the intake structure, diesel generator building, and main stack outside the powerblock area. For this case study, only the powerblock area will be considered.

The powerblock area is shown in plan view in Figure 2. All of the structures considered were either seismic Category I or related structures. The settlement study entailed computing the minimum or limiting allowable differential settlement of each structure and comparing this with measured values of settlement.

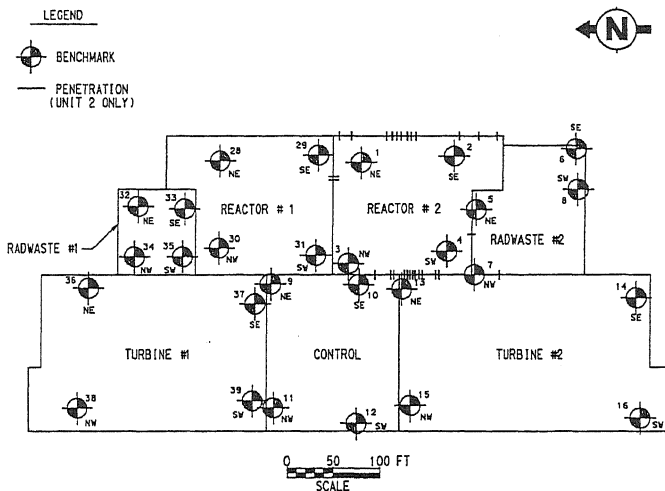


Fig. 2 Plan of Powerblock Area

Foundation Conditions

The site topography prior to construction was gently rolling, with elevations ranging from about 125 to 145 feet MSL with a finished plant grade of 129 feet MSL. The plant site is part of the Atlantic Coastal Plain physiographic province. Relatively unconsolidated materials at the site extend approximately 4,000 feet to a basaltic basement rock of pre-Cretaceous age. No structural features offset the material underlying the site nor do any major or minor fault zones exist near the site.

In the powerblock area, the predominant foundation soils are medium dense to very dense clayey fine sands, extending to about zero elevation; clay layers are found throughout much of the stratum and the sand is partially cemented between about Els. 120 and 75 feet MSL. Hard silty clays exist below the clayey sand. The powerblock structures are built on mat foundations, the deepest being that of the reactor at El. 74 feet MSL. A subsurface profile through a portion of the powerblock structures is shown in Figure 3.

Two distinct water levels exist within the upper formations. The upper (unconfined) level is a "perched" water table which roughly parallels the surface topography running 5 to 20 feet below the ground surface. The lower (confined) aquifer exists below about El. 110 feet; the natural potentiometric surface in this aquifer is around El. 70 feet in the powerblock area.

Predicted Settlements

The predicted settlement was computed using an equation based on elastic theory (Bowles, 1968) with an average elastic modulus value. This modulus was estimated from laboratory unconsolidated undrained (UU) and consolidated undrained (CU) triaxial shear tests and also from field standard penetration test N-values. The foundation soils were modeled as one layer with a single modulus value, resting on a rigid base. Total settlements

of the reactor buildings for Units 1 and 2 were predicted at about 2.5 inches. Predicted or estimated differential settlements were on the order of 0.75 to 1 inch.

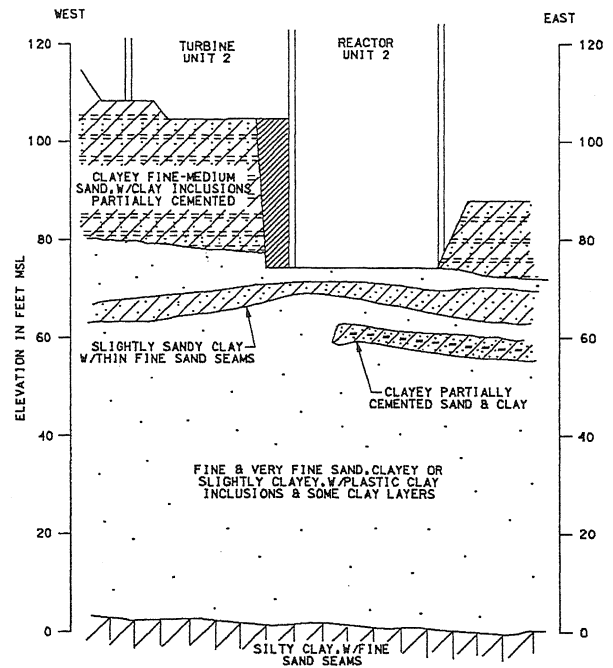


Fig. 3 Typical Subsurface Conditions

Allowable and Measured Differential Settlements

Allowable differential settlements (tilt) across and between structures were computed by the methods explained previously. Table 1 summarizes the differential settlements allowed across each structure in each direction. Prevention of buildings touching during an earthquake governs allowable tilt in the powerblock area. Outside the powerblock area, the allowable tilt is limited by structural and architectural considerations. Computation of the amount of tilt tolerable to installed equipment was beyond the scope of this paper. Table 2 shows the differential settlements allowable for penetrations between Unit 2 reactor and turbine buildings. Similar calculations were made for penetrations between other buildings in the powerblock, and between buildings and the soil. For the majority of the penetrations, the anchor system governs the amount of settlement allowed. A summary of the critical differential settlements between adjacent powerblock buildings and between buildings and soil are shown on Table 3.

The locations of the settlement markers are shown in Figure 2. In some cases, the original markers were preserved. In other instances, the markers had to be transferred to make them accessible as construction proceeded. Sometimes the location of the marker was preserved, but the original bolt had to be replaced, resulting in a small change of levels. The elevations of the markers were normally recorded once a month,

but sometimes at longer intervals. Note that settlement markers could not be placed at the center of each structure; thus, no record is available of possible center sag and its relation to structure rigidity.

variations associated with optical surveying, including seasonal variation with temperature. A similar pattern was noted for the other buildings.

TABLE I. Summary of Differential Settlements Across Structures

Structure	Reference Date	Direction Of Tilt	Between Benchmark Numbers	Differential Settlement Inches		Ratio Of Measured To Allowable Percent
				Allowable	Measured	
Reactor Building Unit No. 2	5-76	N-S	1 and 2	0.40	0.01	3
		N-S	3 and 4	0.41	0.02	6
		E-W	1 and 3	1.67	0.12	9
		E-W	2 and 4	1.61	0.11	7
Radwaste Building Unit No. 2	10-75	N-S	5 and 6	1.85	0.30	16
		N-S	7 and 8	1.92	0.30	16
		E-W	5 and 7	1.58	0.02	2
		E-W	6 and 8	0.96	0.02	3
Control Building	1-75	N-S	9 and 10	1.00	0.07	7
		N-S	11 and 12	0.95	0.16	16
		E-W	9 and 11	3.01	0.23	8
		E-W	10 and 12	3.46	0.14	4
Turbine Building Unit No. 2	5-76	N-S	13 and 14	2.69	0.22	8
		N-S	15 and 16	2.46	0.34	14
		E-W	13 and 15	2.96	0.22	7
		E-W	14 and 16	3.37	0.13	3

TABLE II. Summary of Penetration Differential Settlements Reactor Building Unit 2 and Turbine Building Unit 2

Penetration	Reference Date	Nearest Benchmark Numbers	Differential Settlement - Inches			Ratio of Measured to Allowable Percent	
			Measured to Date	Allowable Pipe	Anchor	Pipe	Anchor
10 in. No. 43	5-78	4 and 13	0.08	2.12	1.68	4	5
4 in. No. 44	1-78	4 and 13	0.06	1.30	--	5	--
3 in. No. 57	11-77	4 and 13	0.08	4.17	--	2	--
18 in. No. 57	7-77	4 and 13	0.07	9.55	1.59	1	5
24 in. No. 57 (El. 154.46)	9-76	4 and 13	0.19	25.13	10.59	1	2
24 in. No. 57 (El. 154.55)	9-76	4 and 13	0.19	22.54	9.05	1	2
8 in. No. 84	2-77	4 and 13	0.10	1.13	1.01	8	10
10 in. No. 90	1-78	4 and 13	0.06	2.51	1.77	2	3
3 in. No. 92	12-77	4 and 13	0.04	1.78	1.55	2	2

Figures 4 and 5 show the marker settlement profiles for the Unit 1 and 2 reactor buildings, respectively, from the start of construction to the present. After about June 1977, the general downward settlement trend ceased with no measurable movement taking place. The slight cyclic movements taking place are probably due to the inherent

A comparison of calculated allowable and actual measured differential settlements is also included in Tables 1 through 3. For tilt of the buildings, the ratio of allowable to measured settlement is less than 20 percent in all cases. Since present trends (see Figures 4 and 5) indicate only a small increase, if any, in settlement values, there

TABLE III. Summary of Critical Differential Settlements Between Adjacent Structures and Structures and Soil

Structure to Structure	Reference Date	Nearest Benchmark Numbers	Differential Settlement Inches		Measured to Allowable Percent
			Allowable	Measured	
Reactor 2 to Turbine 2	2-77	4 and 13	1.01	0.10	10
Reactor 2 to Control	1-78	3 and 10	0.62	0.20	32
Reactor 2 to Radwaste 2	11-77	2 and 5	1.07	0.11	10
	2-77	4 and 5	0.88	0.05	6
Reactor 2 to Reactor 1	1-78	1 and 29	0.53	0.05	9
Reactor 2 to Soil	1-78	1	0.72	0.11	15
	1-78	2	0.56	0.18	32

REACTOR BUILDING UNIT 1

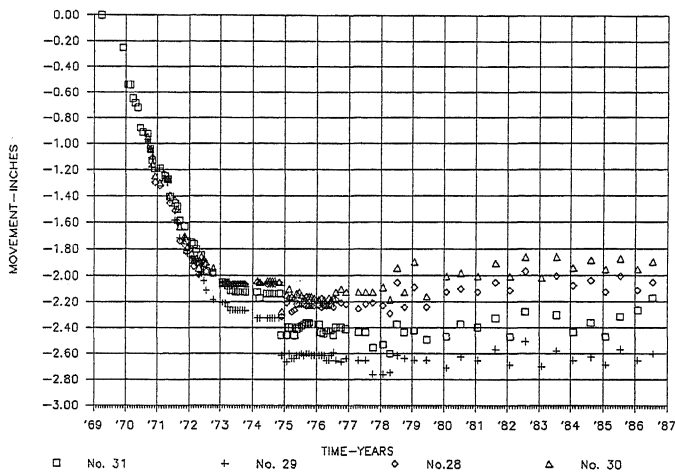


Fig. 4 Reactor Building Settlement - Unit 1

REACTOR BUILDING UNIT 2

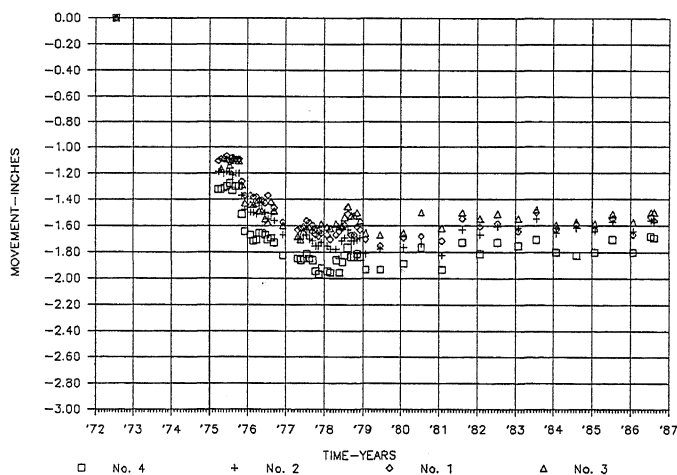


Fig. 5 Reactor Building Settlement - Unit 2

seems to be no cause for concern regarding tilt, either now or in the future. For penetration differential settlements, the ratio of allowable to measured differential

settlement in the majority of cases is less than 20 percent.

Discussion

The case studied provides reassuring results concerning the settlement characteristics and trends at a major nuclear plant. The plant rests on mat foundations on dense clayey sands. Due to these foundation conditions, measured differential settlements are much less than the computed allowable settlements in almost all cases. Assuming present settlement trends continue, there appears to be little chance that structures or penetrations will become overstressed due to differential settlement within the lifetime of the plant. However the study revealed a number of points regarding the design of the plant and the existing settlement monitoring program.

First, the differential settlement modes described in this paper were not specifically taken into account in the design of either the structure or the penetrations. Although predicted differential settlement values were provided by the geotechnical consulting engineer during the plant design, allowable differential settlements were not computed.

Second, there was a lack of consistency in the time of placement of the settlement markers in relation to construction. For most of the structures, the markers were placed in the foundation mat; in some cases, however, markers were placed several floors above the foundation. Comparison of settlement of structures was difficult in these cases.

And third, although marker data were recorded and documented monthly, no backup information was provided. A most useful addition for reviewing and analyzing the marker movements would have been a record of the construction phase and activities at the time of measurement. An attempt could then have been made to correlate settlements with events such as start of excavation for adjacent foundations, end of construction dewatering, etc.

CONCLUSIONS AND RECOMMENDATIONS

This paper has described procedures for obtaining values of allowable differential settlement at a nuclear plant and for measuring actual settlements on a regular basis. A case history of differential settlement at an existing nuclear plant has been presented. The following recommendations are made concerning computation and measurement of differential settlement at nuclear power plants:

- (1) During plant design, in addition to predicting differential settlements of major structures, computations should be made of the allowable differential settlement governed by architectural and structural considerations, equipment design, touching of buildings during an earthquake, and overstressing of penetrations.
- (2) Prior to plant construction, a detailed plan should be developed to place settlement markers in the foundation mats of the major structures. As a minimum requirement, there should be markers at the corners and centers of each structure.

- (3) During and after plant construction, the settlement markers should be monitored on a monthly basis. The monthly report should contain all relevant information on construction activities relating to the major structures. The settlement data should be plotted versus time, and then reviewed by a geotechnical engineer who is familiar with the foundation design and subsurface conditions. Whenever differential settlement at a marker consistently accelerates over a period of months, or measured differential settlement reaches 75 percent of the allowable value, an engineering investigation should be performed to find the causes of settlement and if remedial action is necessary.

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