Earthquake analysis and engineering feasibility study for the Gentilly-3 nuclear station

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ABSTRACT: This paper presents an engineering feasibility study which has been performed for a third nuclear station at the Gentilly site in Quebec. The station is to consist of 4 reactor building units 850 MWe capacity each, serviced by one common vacuum building. In the study, two basic structural layouts for each of the reactor and vacuum buildings were considered and the structures were analyzed for two different levels of earthquake intensities, 0.15 g and 0.30 g maximum horizontal ground acceleration for design basis earthquake. For seismic analyses, a number of 2-D and 3-D lamped parameter (stick), and finite element axisymmetric models were developed, taking into account different aspects such as soil-structure-interaction, radiation and composite dampings, and fluid-structure-interaction (sloshing effect). The analysis results assured the technical feasibility of the project and established the additional costs involved.

1 INTRODUCTION

Many projects have been undertaken without a proper feasibility study, or with a study where its conclusions were either ignored or erroneous. Practice demonstrates that a rational approach to project viability is an important requirement. There are variety of types of feasibility studies or analyses that can be commissioned, featuring different mandates and objectives. This paper considers only the engineering aspects associated with a preliminary study for a nuclear power plant and provides, through approximate design and cost estimation, the necessary input data for a financial feasibility.

Unquestionably, especially for projects involving large committments of resources, commissioning a detailed feasibility study is a prudent investment, particularly when the cost of these studies represents a relatively small percentage of the total anticipated project cost (often less than 1%).

This paper presents the seismic analyses needed as an essential part of the engineering feasibility study required to establish whether or not a third nuclear station of a particular type could be constructed at the Gentilly site in Quebec. The study was commissioned with a mandate from Hydro Quebec to investigate the possibility of constructing a nuclear power station of Hydro Ontario's Darlington-A type, consisting of four reactor building units, 850 MWe capacity each, serviced by one common vacuum building.

The site at Darlington-A station, refered to later as the "reference plant", is characterized by a much lower level of seismic intensity coupled with very stiff foundation rock media as compared to the Gentilly site. The maximum ground horizontal acceleration of the design basis earthquake (DBE) is 0.08 g at Darlington site, while for the new Gentilly station the seismic analyses were required to be performed under two levels, 0.15 g (Gentilly-3, alternative 1) and 0.30 g (Gentilly-3, alternative 2). Upon establishing the technical feasibility of the two alternatives, it was then required to estimate the additional costs of the civil works over those of the reference plant.

2 STRUCTURAL ALTERNATIVES

The investigated nuclear station consists basically of a row of four reactor buildings surrounded by auxiliary facilities and connected to a central vacuum building by a fuel tunnel and a pressure release conduit as shown in Figures 1 and 2.

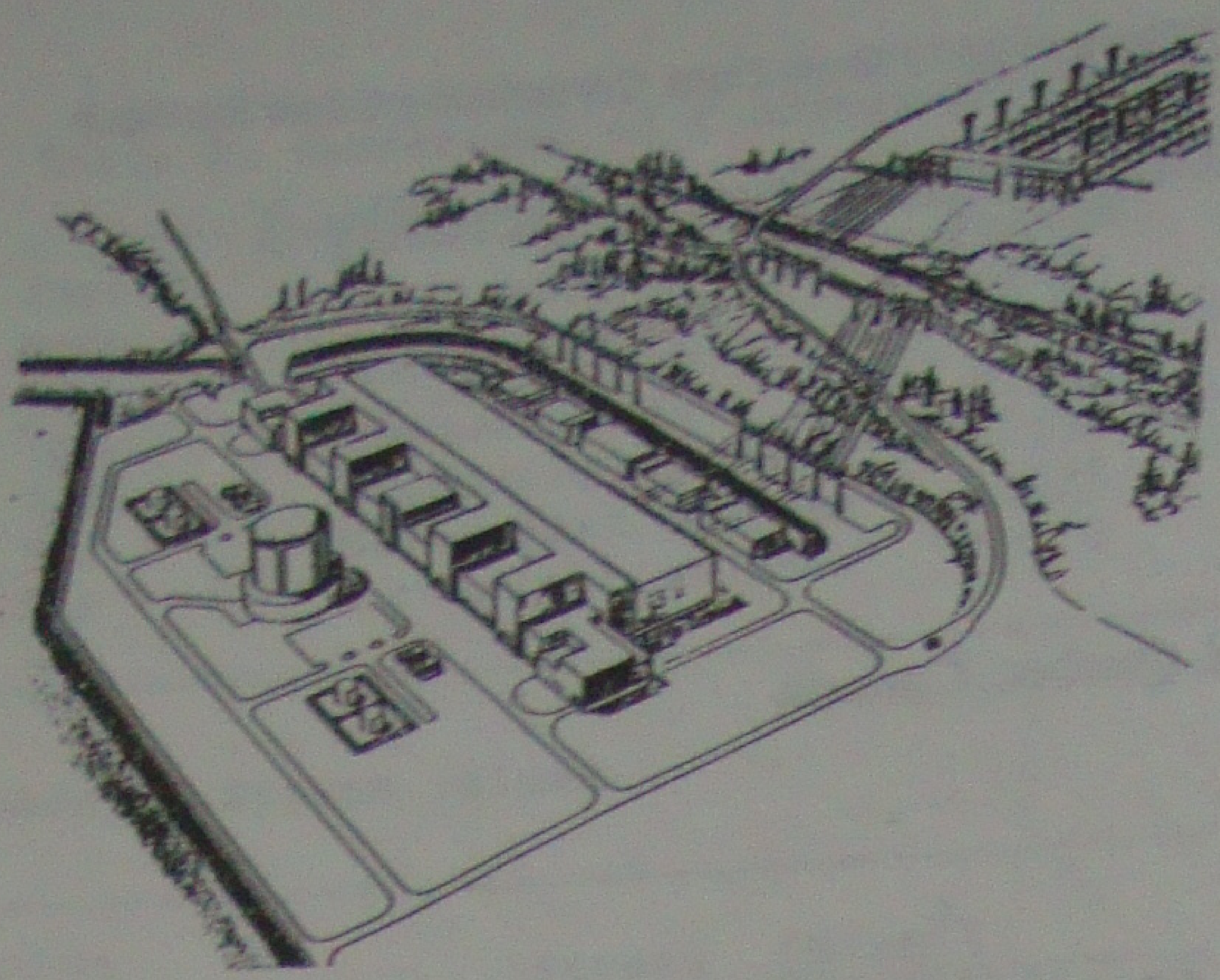

Fig. 1 General View

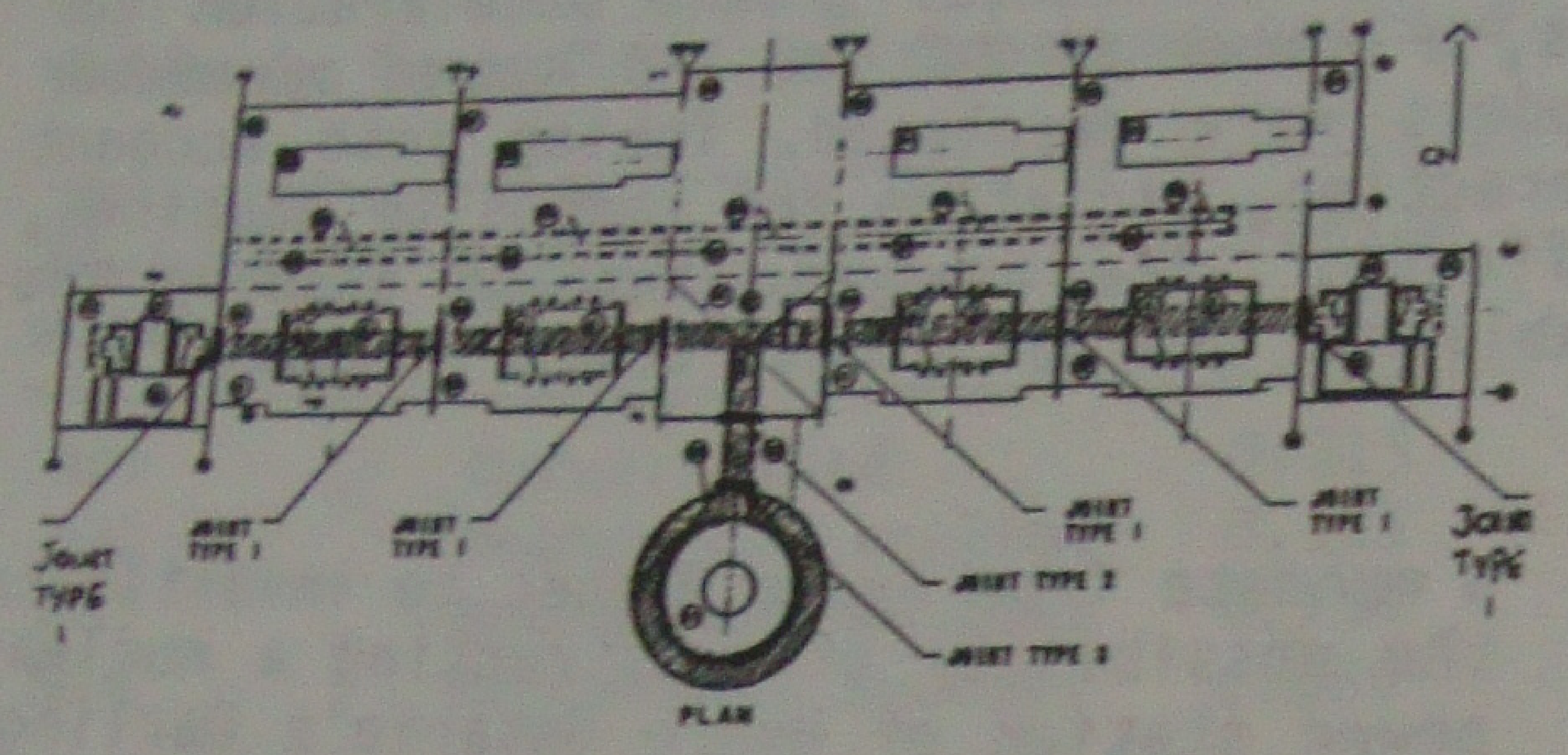

Fig. 2 General layout

Due to the less advantageous soil conditions at Gentilly site as compared to the reference plant site, two basic structural layouts were considered in the present study for each of the reactor building and the vacuum building. In the first arrangement, a common base slab was considered to support the reactor and surrounding auxiliary buildings on one hand, and to support the vacuum building and the surrounding pressure release conduit on the other. In the second arrangement, however, an isolated base slab was considered for each of the reactor building and the vacuum building.

It is evident that each of the two arrangements possesses its own advantages and disadvantages as related to engineering and cost aspects, which are to be assessed in view of the characteristics of the present station in an effort to establish an optimum solution. A larger common base slab will generally reduce the seismic responses of the supported structures, reduce the soil bearing pressures, and improve the overall stability, while it will attract higher design forces requiring larger cross-sectional dimensions.

3 SEISMIC ANALYSIS MODELS

Earthquake analysis has been performed on all the pressure related structures and components of the nuclear part of the station. A number of models have been developed for a typical reactor building unit and the central vacuum building.

For the reactor building and the surrounding auxiliary building (Figure 3), two lumped parameter models have been developed.

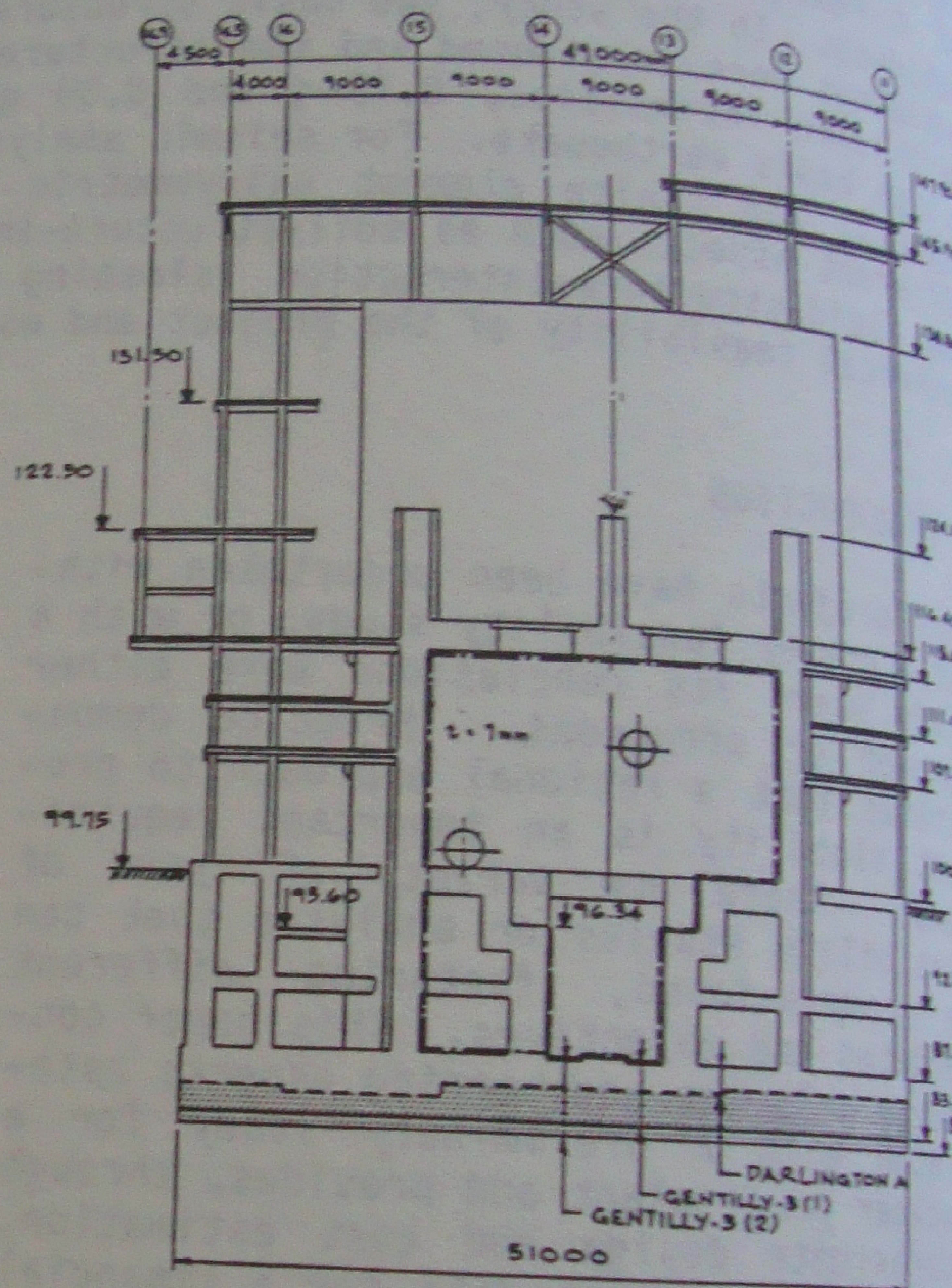

Fig. 3 Cross-sectional elevation - reactor building

The first corresponds to the combined base arrangement (Figures 4.a and 4.c) which incorporates the entire auxiliary building. The second is similar, but accounts only for a part of the auxiliary building and corresponds to the isolated base arrangement shown in Figure 4.b.

In these 3-D stick models, the top structural steel part and the underneath reinforced concrete shear walls were represented by frame elements having the normal 6 D.O.F. per node. Due attention was given to incorporate the shear deformation mode of concrete walls and structural steel bracings.

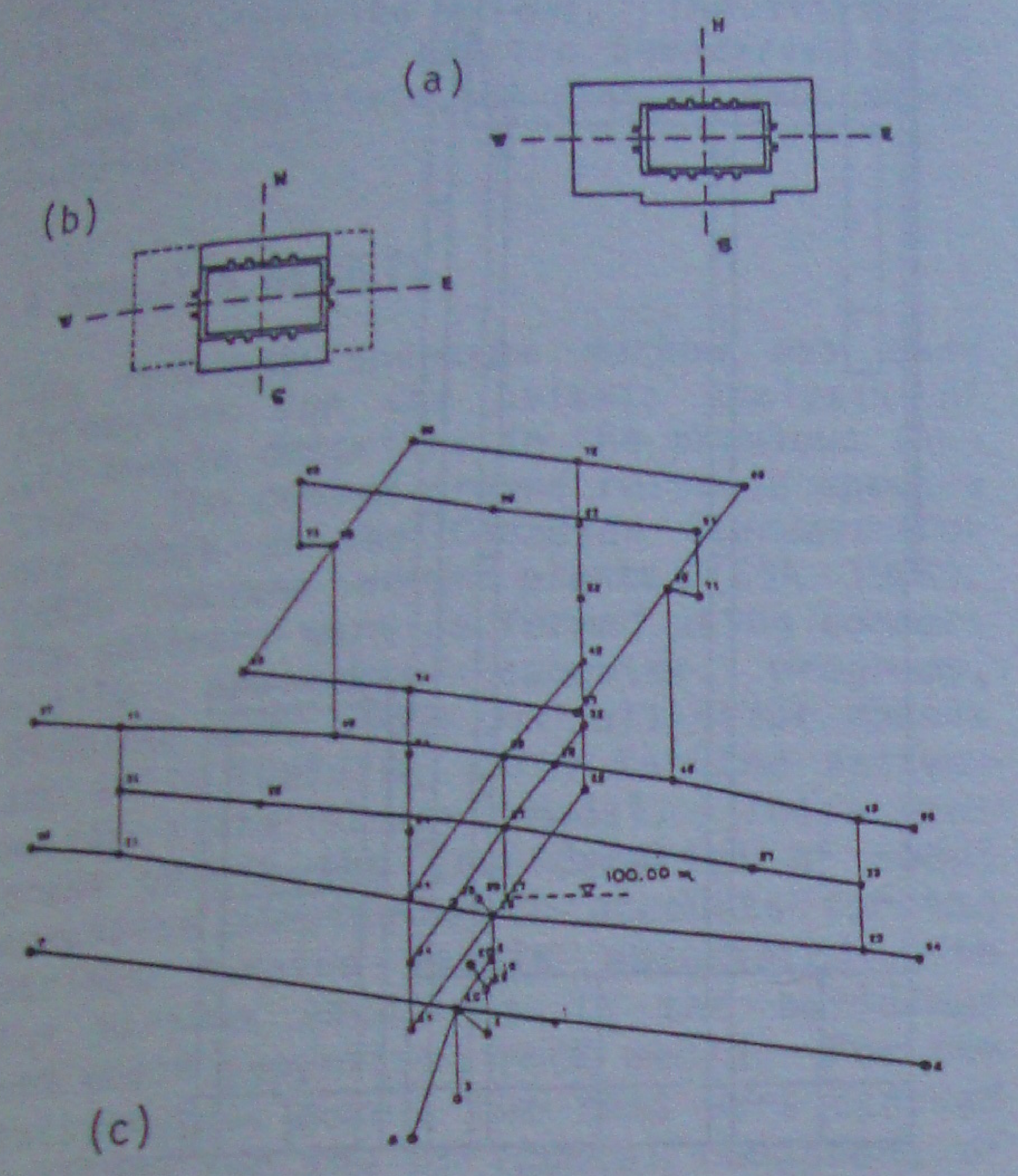

Fig. 4 Analysis model for the reactor building:
 a. reactor building on combined base
 b. reactor building on insulated base
 c. stick model for the combined base alternative

The base slab was assumed rigid and mounted on equivalent soil springs incorporating the stiffness and damping of the supporting rock media. The Gentilly site is characterized by a layered rock and the corresponding stiffness coefficients and damping ratios were calculated using an in-house computer program (Daly and Iordanescu 1982) based on the superposition method proposed by Johnson (1975). The soil-structure-interaction idealization was further improved by incorporating the radiation damping corresponding to the semi-infinite extent of the supporting rock in addition to its material damping (Richard, etal 1970). The geometry has been preserved in the models by introducing additional nodes at characteristic locations, particularly at the periphery where relative displacements between adjacent buildings have to be evaluated. Masses were lumped at floor levels including the rotational inertia effects. Mass calculation was based on dead loads and one half of live loads (CSA 1981).

For the prestressed concrete vacuum building, the isolated base arrangement was found to produce excessive bearing pressure beyond the allowable limits for both of the 0.15 g DBE and 0.30 g DBE alternatives, and as such was ruled out in the early stage of this study. For the combined slab arrangement which integrates the surrounding pressure release conduit with the vacuum building on a common mat (Figure 5), two types of models were developed.

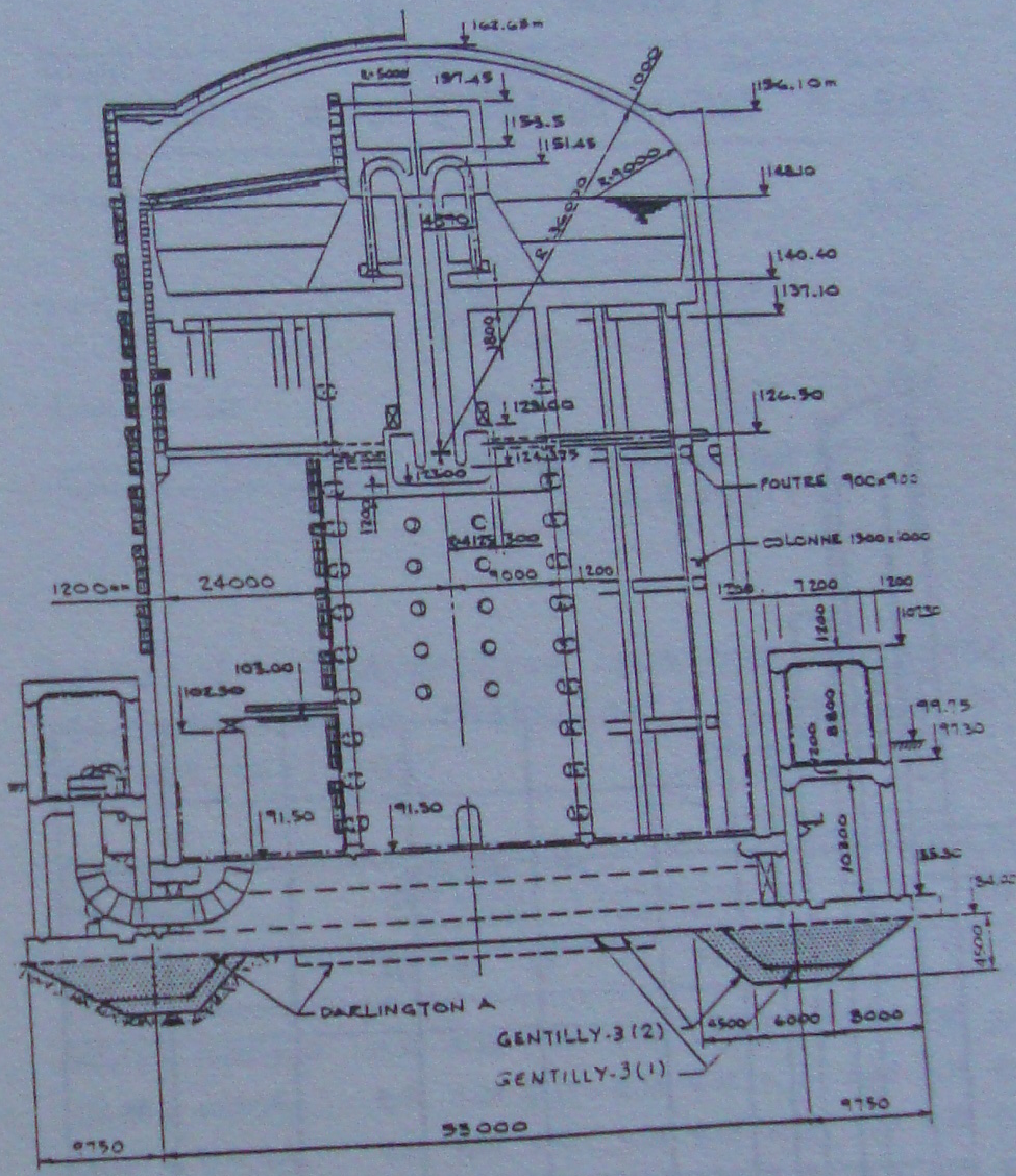

Fig. 5 Cross-sectional elevation - vacuum building

The two models complement and verify each other and together furnish the relevant information needed for the design process as described by Mamet and Moselhi (1985). The first is a 2-D lamped mass model (Figure 6) developed basically to generate base shear, up lift force and overturning moment required for the verification of the overall stability of the structure. The second is a finte element axisymmetric representation (Figures 7 and 8.a) incorporating the supporting rock media, needed

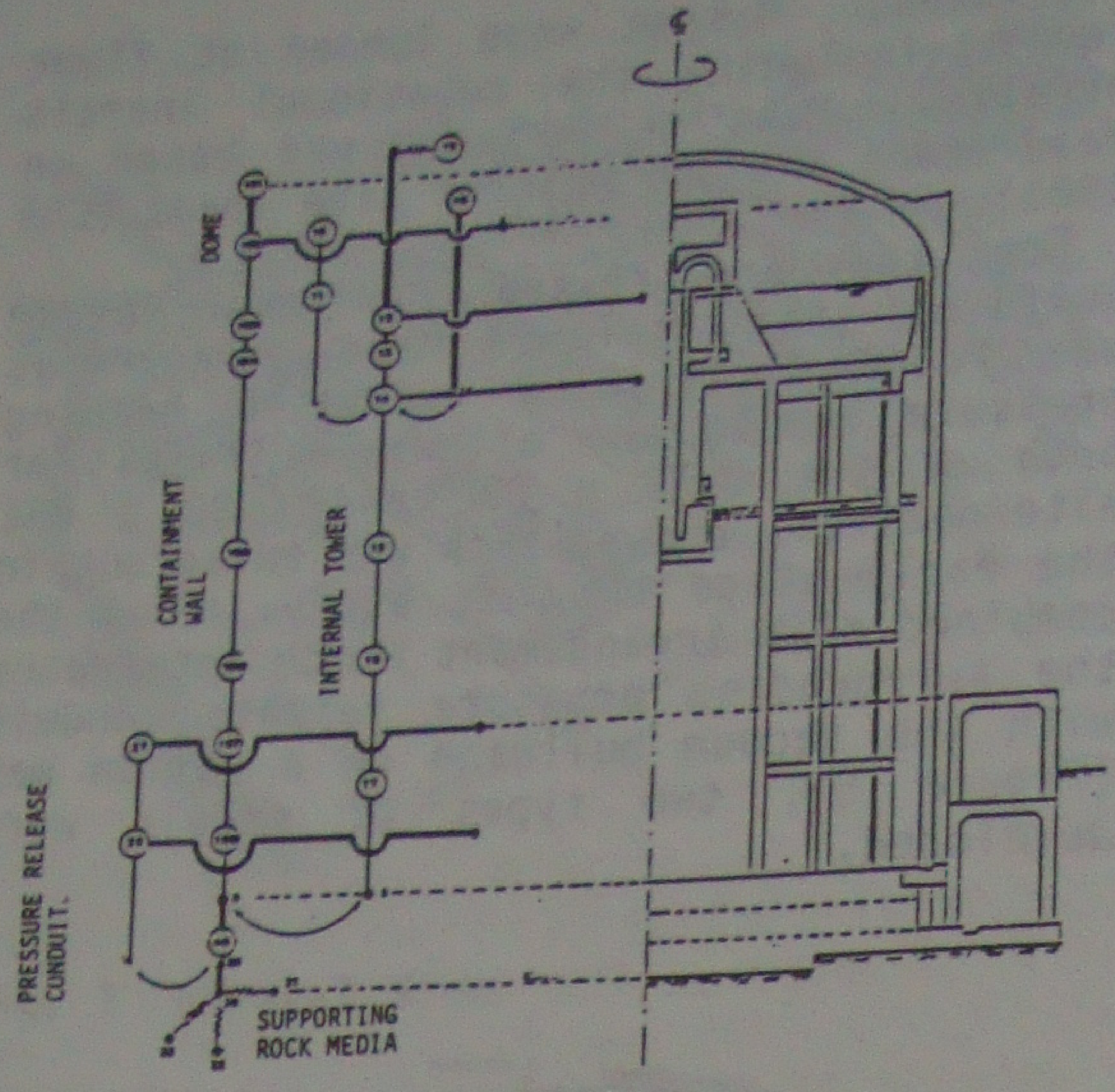

Fig. 6 Vacuum building stick model

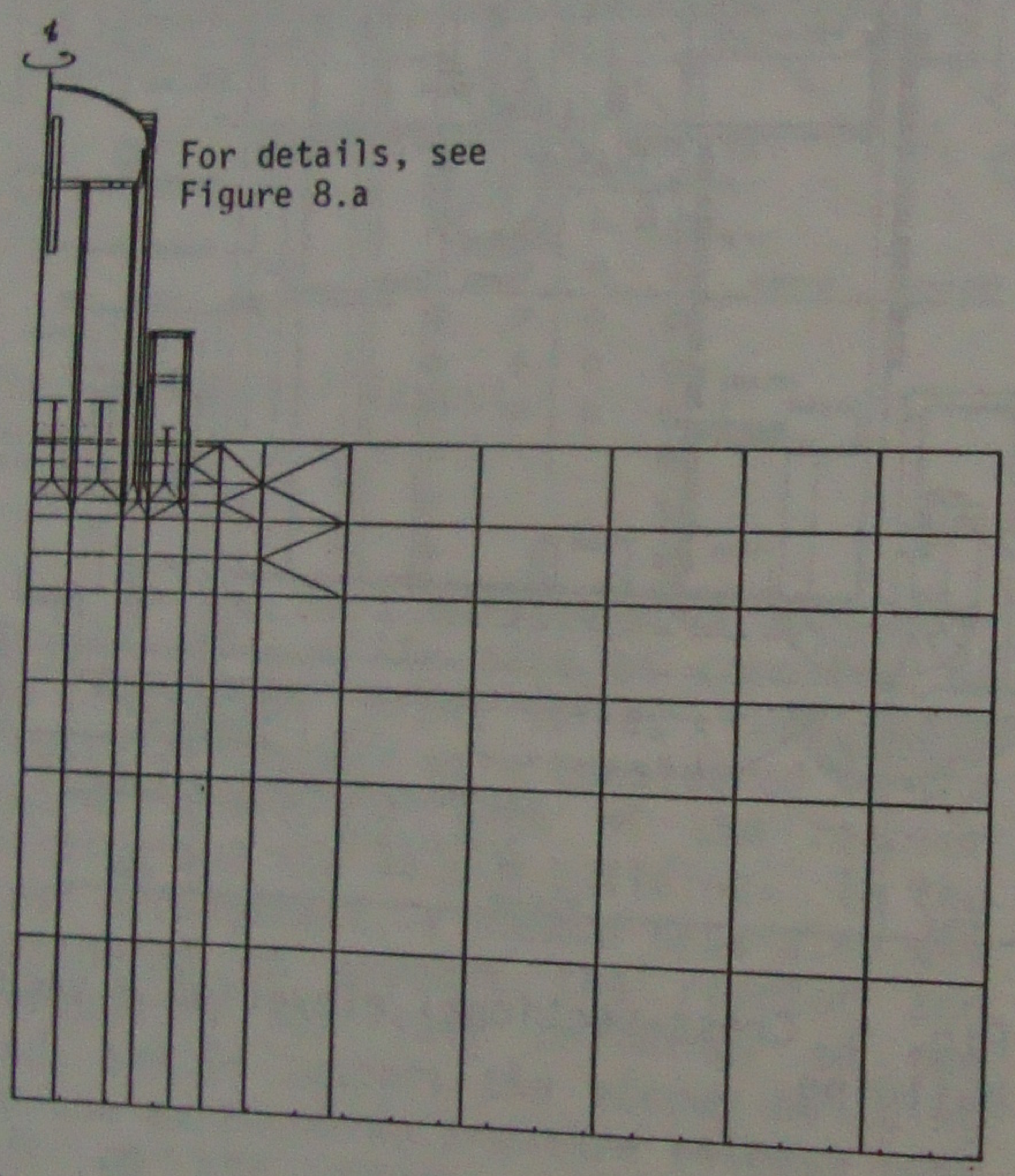

Fig. 7 Vacuum building axisymmetric model

to obtain the detailed maximum forces in containment (dome, wall, base slab, internal water tank) and establish the distribution of the soil bearing pressures.

Both models incorporate an equivalent mass-spring representation for the sloshing effect of the dousing water in the internal tank. The models, however, differ in the soil-structure-interaction representation. The stick model assumes a rigid base mounted on equivalent soil springs in a similar way to that described earlier for the reactor building model.

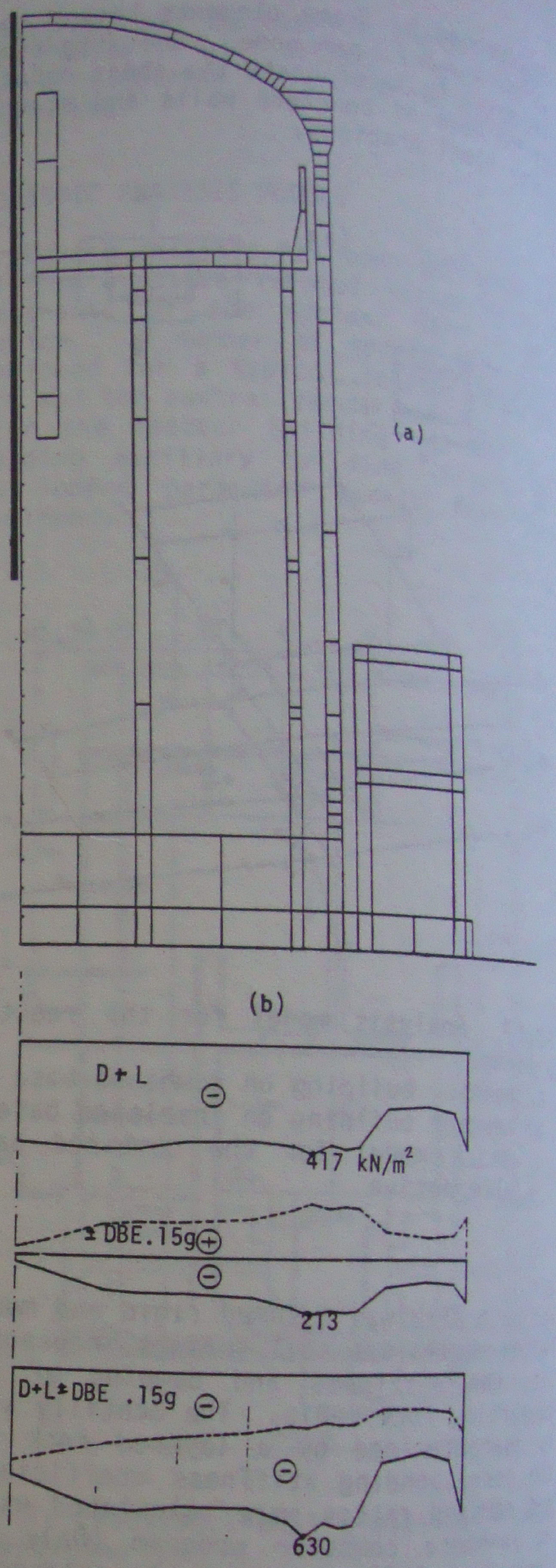

Fig. 8 Bearing soil pressure under the vacuum building for basic load combinations

The axisymmetric model includes an elastic base slab mounted on a grid of rock finite elements. Equivalent elastic springs were introduced at the horizontal and vertical boundaries of the finite representation of the rock to account for its semi-infinite extent. The stiffness values of these elastic boundaries were tuned to duplicate the elastic half space behavior.

4 ANALYSIS RESULTS

The response spectrum method was used throughout for the seismic analysis of all models described in the previous section. The design ground response spectra are those of the Canadian Standard for CANDU nuclear power plants (CSA 1981). The analyses were performed using commercially available computer programs, STARDYNE (CDC 1980) for all stick models and ANSYS (DeSalvo 1978) for the axisymmetric finte element model. These programs permit the consideration of modal composite damping which accounts for the various damping levels associated with the various materials in the buildings and their supporting rock media. For the axisymmetric model, two runs were carried out: one for the horizontal component of the earthquake and the other for the vertical component, by assigning different dynamic degrees of freedom.

Using a number of in-house computer programs, the analysis results were then post-processed and load combinations generated according to the code and current practice requirements (ASCE 1980, CSA 78, CSA 81, and Mamet and Moselhi 1985).

Sample of the free vibration analysis results and for the maximum response accelerations and displacements for the reactor and vacuum buildings are presented in Tables 1 to 6. For the reactor building, a comparison is made between models with and without the soil-structure-interaction effect, and for models with isolated and combined base slab. For the vacuum building, the results of the stick models are compared to those obtained from the axisymmetric finite element model.

A number of design verifications were then carried out. A major concern was related to the soil bearing pressure and the overall stability safety factors. The stability of the buildings was verified against overturning, sliding, and uplifting under different seismic levels and ground water tables. Figure 8.b illustrates the distribution of the soil bearing pressure for the combined base arrangement of the vacuum building associated with the basic load combinations. The first diagram corresponds to the case of dead plus live loads, the second to 0.15 g DBE conditions, and the third combines these two. Similar to the vacuum building, the results obtained for the reactor building indicate that the isolated base arrangement is not feasible even for the 0.15 g DBE level due to excessive bearing pressure and inadequate stability safety factors.

Table 1. Comparative modal characteristics - modal frequencies and associated composite damping ratios for reactor building

Natural modes of vibration	Isolated base with SSI*	Combined base	
		fixed	with SSI
First horizontal N-S	2.79 HZ (15.7%)	3.31 (5%)	3.04 (12.5%)
First horizontal E-W	2.86 (14.6%)	3.35 (5%)	3.19 (10.3%)
First Vertical	4.74 (28.8%)	15.39 (5%)	4.88 (28.8%)

*Soil-structure-interaction

Table 2. Comparative maximum response accelerations at characteristic levels for reactor building

Elevation and location	Reference plant (DBE 0.08g) fixed base			Gentilly-3 (DBE 0.15g)					
				combined base			isolated base		
	X1*	X2	X3	X1	X2	X3	X1	X2	X3
145.90 m, steel roof	0.43	0.38	0.45	1.92	1.79	0.21	1.39	1.57	0.19
138.80 m, concrete	0.39	0.38	0.12	0.33	0.32	0.15	0.13	0.35	0.15
116.40 m, concrete	0.23	0.17	0.07	0.23	0.20	0.14	0.20	0.20	0.15
100.00 m, concrete	0.11	0.08	0.05	0.17	0.15	0.12	0.15	0.15	0.12
87.70 m, Base slab	0.08	0.08	0.05	0.15	0.16	0.17	0.15	0.15	0.17

*X1 - Horizontal absolute acceleration (g) E-W
X2 - Horizontal absolute acceleration (g) N-S
X3 - Vertical absolute acceleration

Preliminary structural design was performed at a number of critical locations for the reactor and vacuum buildings. As expected, additional cross-sectional dimensions over those of the reference plant were needed and determined seperately for the two earthquake levels considered. In the reactor building, the main additional material quantities were in the reinforced concrete base slab and shear walls (Figure 3). In the vacuum building, the main modifications were related to the increase of the level of prestressing in the containment dome and wall and local increase of the base slab thickness under the containment wall (Figure 5).

Table 3. Comparative maximum response displacements at characteristic levels for reactor building

Elevation and location	Reference plant (DBE 0.08g) fixed base			Gentilly-3 (DBE 0.15g) combined base			isolated base		
	X1*	X2	X3	X1	X2	X3	X1	X2	X3
145.90 m, steel roof	0.86	0.78	.05	4.32	4.19	0.2	3.59	4.02	0.31
138.80 m, concrete	0.24	0.18	0.02	0.62	0.71	0.16	0.92	0.90	0.25
116.40 m, concrete	0.14	0.06	0.02	0.45	0.43	0.16	0.58	0.56	0.24
100.00 m, concrete	0.05	0.02	0	0.31	0.26	0.13	0.34	0.35	0.13
87.70 m, Base slab	0	0	0	0.21	0.17	0.21	0.20	0.21	0.29

*X1 - Horizontal relative displacement (cm) E-W
X2 - Horizontal relative displacement (cm) N-S
X3 - Vertical relative displacement

Table 4. Comparative modal characteristics - modal frequencies and associated composite damping ratios for vacuum building

Natural modes of vibration	Reference plant fixed base stick model	Gentilly-3 with SSI*	
		stick model	axisymmetric model
Dousing Water Sloshing	0.105 HZ (0.5%)	0.105 (0.5%)	0.105 (0.5%)
First horizontal Internal tower	2.19 (5%)	1.99 (7.8%)	1.62 (6.6%)
First horizontal Containment wall	4.51 (3%)	3.24 (9.4%)	2.83 (9.25%)
First Vertical	7.52 (5%)	4.67 (25.5%)	4.35 (19.9%)

*Soil-structure-interaction

Table 5. Comparative maximum response accelerations (g) at characteristic levels for vacuum building

Location	Reference plant stick model		Gentilly-3 (DBE 0.15g) stick model		axisymm. model	
	H*	V	H	V	H	V
Top of dome	0.35	0.13	0.48	0.14	0.49	0.18
Ring beam	0.33	0.19	0.44	0.22	0.45	0.22
Water tank slab	0.19	0.23	0.41	0.38	0.33	0.75
Top of pressure release conduit	0.16	0.05	0.19	0.16	0.26	0.11
Base slab	0.08	0.05	0.15	0.11	0.18	0.11

*H - Horizontal absolute acceleration
V - Vertical absolute acceleration

Table 6. Comparative maximum response displacements at characteristic levels for vacuum building

Location	Reference plant stick model		Gentilly-3 (DBE 0.15g) stick model		Axisymm. model	
	H*	V	H	V	H	V
Top of dome	0.43	0.02	1.25	0.15	1.51	0.17
Ring beam	0.40	0.02	1.17	0.38	1.40	0.44
Water tank slab	0.98	0.57	2.50	1.36	3.00	0.77
Top of pressure release conduit	0.02	0.003	0.33	0.31	0.29	0.20
Base slab	0	0	0.18	0.12	0.19	0.19

*H - Horizontal relative displacement (cm)
V - Vertical relative displacement (cm)

The structural integrity of the various segments of the fuel tunnel and the pressure release conduit (Figure 2) was verified with emphasis on the relative displacement between adjacent buildings. It was found that a steel liner is needed throughout as well as bellows at all joints between the various segments.

The design verifications performed enabled the determination of the additional quantities needed for construction and yielded the estimated increase in cost of the station over that of the reference plant. The cost estimate has been prepared only for civil works. Although earthquake floor response spectra have been generated at characteristic locations in the reactor building, the estimate of the additional equipment costs is beyond the scope of the present study.

5 CONCLUDING REMARKS

Based on the analysis performed, the design effort conducted, and the estimation of material quantities and overall cost prepared, the following conclusions were made:

a. It is technically feasible to design and construct the various structures of the Darlington-A type nuclear power station at Gentilly site, even with the differences associated with seismic intensity and supporting soil characteristics.

b. It is not technically feasible to construct any of the reactor building units nor the central vacuum building using the isolated base slab arrangement. It has been found that a common base slab supporting each of these respective buildings and their surrounding facilities is required.

c. The additional material cost of the Gentilly-3's four reactor buildings, vacuum building and connecting tunnel structures over that of the reference plant is estimated at 0.6% of the total plant cost for the seismic case of 0.15 g DBE, and 1.33% for the seismic case of 0.30 g DBE.

d. The floor response spectra generated in the present study (not shown here) could be used to asses further additional costs for the equipment and piping of the station.

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