INFO 0039

Report Rappo

Atomic Energy Control Board

Commission de contrôle de l'énergie atomique

CA8205527

INFO-0039

HISTORIC EASTERN CANADIAN EARTHQUAKES
A REAPPRAISAL OF NEAR-FIELD EFFECTS

by

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10 June 1981

This paper was presented at the 2nd Annual Conference of the Canadian Nuclear Society, June 10, 1981, in Ottawa, Ontario.

ABSTRACT

Nuclear power plants licensed in Canada have been designed to resist earthquakes: not all plants, however, have been explicitly designed to the same level of earthquake induced forces. Worldwide, the level of earthquake resistance demanded from NPP's, by both the nuclear industry and the regulatory authorities, has increased dramatically over the last 15 years: where figures are available the cost of earthquake protection has added a minimum of three percent to the direct cost of the plant.

Confidence in the level of earthquake protection provided is a function of (a) the severity and nature of the postulated ground shaking at the site and (b) the complexity and accuracy of the mathematical analysis of structure and equipment. The former is by far the most difficult to quantify and particularly so for earthquakes postulated to occur close to the site. In the last three years the data base on near-field earthquake excitation has increased considerably; improved theoretical understanding can be expected in the next few years. The recent records show that near-field ground accelerations and veolocities may be several times higher than would be predicted using currently accepted formulas; however, these larger values have apparently not caused extensive damage. Such higher values of acceleration and velocity may be enhanced by focussing of energy associated with failure propagation and constructive interference of wave packets from discreet bursts of energy. We know of no quantifiable information pertaining to the phenomenon of amplification which is specific to Eastern Canada; however, from published data originating elsewhere we conclude that if an earthquake of moderate size or larger, $M > 5.0$, were to occur within 30 km of a Canadian NPP, the design basis earthquake may be exceeded.

Understanding the nature of strong ground motion near the source of the earthquake is still very tentative. The purpose of this paper is to record the efforts that have gone on to-date and to add a stimulus for future research. Our investigation has been three-fold:

a) review of historical and scientific accounts of the three strongest earthquakes - St. Lawrence (1925), Temiskaming (1935), Cornwall (1944) - that have occurred in "modern" times, followed by interviews with then residents of Temiskaming and Cornwall.

b) Field studies of near-field strong ground motion records and their resultant damage or non-damage to industrial facilities.

c) Numerical modelling of earthquake sources and resultant wave propagation to produce accelerograms consistent with the above historical record and field studies.

This paper neither condemns nor applauds current earthquake protection provided in Canadian NPP's but it does conclude that for future construction of NPP's near-field strong motion must be explicitly considered in design.

RÉSUMÉ

Les centrales nucléaires pour lesquelles on a octroyé une licence au Canada sont conçues de manière à résister aux tremblements de terre: elles n'ont toutefois pas toutes la même résistance. Dans le monde entier, le niveau de résistance aux séismes exigé des centrales nucléaires, tant par l'industrie elle-même que par les instances de réglementation, s'est accru considérablement depuis 15 ans: dans le cas de centrales pour lesquelles des données sont disponibles, le coût de protection séismique ajoute au moins trois pour cent au coût direct de l'installation.

La confiance accordée au niveau de protection séismique est fonction a) de la gravité et de la nature des tremblements anticipés du sol sous la centrale, et b) de la complexité et de l'exactitude de l'analyse mathématique des constructions et du matériel. Les deux premiers éléments sont de loin les plus difficiles à quantifier, particulièrement lorsque les séismes se produisent à proximité du site. Au cours des trois dernières années, la base de données sur les excitations séismiques à proximité d'un site donné a sensiblement augmenté; la théorie devrait être mieux comprise, d'ici quelques années. Les enregistrements récents révèlent que l'accélération et la vitesse des ondes dans le sol à proximité d'un site peuvent être plusieurs fois plus élevées que les prévisions établies au moyen des formules couramment admises; ces valeurs plus grandes n'ont cependant pas causé de grands dommages, du moins semble-t-il. De telles valeurs supérieures d'accélération et de vitesse de propagation pourraient être relevées du fait d'une concentration de l'énergie associée à une propagation de fractures dans le sol et à l'interférence constructive de paquets d'ondes libérées lors de sursauts d'énergie. Nous ne connaissons aucune information quantifiable ayant trait au phénomène d'amplification qui soit propre à l'Est du Canada. Néanmoins, à partir de données provenant d'autres sources, nous concluons que si un séisme d'importance moyenne ou grande, c'est-à-dire dont la magnitude dépasserait 5,0, se produisait dans un rayon de 30 km autour d'une centrale nucléaire au Canada, le modèle utilisé pour la conception ne serait peut-être pas suffisant.

Nos connaissances relatives à la nature de fortes secousses du sol près de la source du séisme sont encore incertaines. Le document a pour objet de faire état des tentatives qui ont été faites en ce sens jusqu'ici et d'encourager la recherche future. Notre étude se divise en trois volets:

a) Revue de l'historique et des comptes rendus scientifiques des trois séismes les plus importants - Saint-Laurent (1925), Témiscamingue (1935), Cornwall (1944) - qui se sont produits "récemment", suivie d'entrevues avec les résidents d'alors de Témiscamingue et de Cornwall.

b) Etudes sur le terrain des enregistrements de fortes secousses du sol à proximité d'un site et des dommages, si dommages il y a, qui en ont résulté dans des installations industrielles.

c) Modèle numérique des sources de séismes et de la propagation consécutive des ondes afin de produire des accélérogrammes qui correspondent à l'historique et aux études sur le terrain.

Ce document ne prétend ni condamner ni louer la protection actuellement offerte par les centrales nucléaires canadiennes contre les tremblements de terre, mais il conclut qu'à l'avenir, les forts mouvements du sol à proximité des centrales devront être explicitement pris en considération dans la conception des constructions.

HISTORIC EASTERN CANADIAN EARTHQUAKES
A REAPPRAISAL OF NEAR-FIELD EFFECTS

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INTRODUCTION

It is an intuitive assumption that the closer one gets to the source of an earthquake the more intense its effects. Furthermore, one would expect that the intensity would be related to several factors such as: the velocity of rupture propagation, the orientation of the rupture surfaces, the energy stored within the rock, and frictional properties. There has been a continuing concern that near the source, complex wave phenomena such as focussing, constructive interference, and localized high stress drops, due to the rupturing process, may cause ground accelerations and velocities far in excess of those hitherto observed in the limited data bank of strong motion records. In the absence of pertinent records, theoretical and numerical calculations had been carried out to illustrate the phenomenon associated with near-field effects. Then, with Diablo Canyon Nuclear Power Plant, interest in the study of near-field effects was intensified both by the utility, the Pacific Gas and Electric Company[1], and by the interveners such as E. G. Brown, Governor of the State of California[2].

In the two year period 1978 to 1979, several exceptionally well recorded earthquakes occurred in Southern California, namely the Gilroy earthquake of August 6, 1979 and the Imperial Valley (El Centro) earthquake of October 15, 1979. These earthquakes have given strong field verification of the theoretically predicted near-field effects.

Logically, one would expect that near-field effects will be manifested near any earthquake, including any eastern Canadian earthquake. However is there any evidence of such effects, and how pertinent are the west coast data to the eastern situation? To answer this question we have (a) reviewed the history of the three strongest earthquakes--St. Lawrence (1925), Temiskaming (1935), Cornwall (1944)--that have occurred in "modern" times; (b) reviewed near-field strong motion records that have been collected by the USGS for the two year period 1978-1979, and carried out field studies to determine the extent of damage and non-damage to industrial facilities; and (c) carried out limited finite difference numerical modelling based on physical properties to simulate accelerograms for near-field motion.

HISTORIC EASTERN CANADIAN EARTHQUAKES

In the 20 year period 1925-1944, three major earthquakes occurred in Eastern Canada--St. Lawrence (M7) 1925, Temiskaming (M6+) 1935, Cornwall (M6-) 1944--which were all widely felt and reported throughout Ontario and Quebec[3]. These earthquakes preceded the era of earthquake engineering in this country so as a result, apparently no engineering studies on the response of structures and equipment were carried out to complement the excellent seismological field reconnaissance studies carried out by the Dominion Seismologist, E. A. Hodgson.

(a) The Cornwall-Massena Earthquake September 5, 1944

The main shock occurred at 0040 hours, Tuesday September 5, 1944, just after midnight following the Labour Day holiday. As there were, of course, no strong motion records of this event, we are left with only the personal impressions of observers at the scene. While these observers perhaps lack quantitative data, they do at least portray the excitement of the event as seen by the following article printed in the local newspaper[4].

"The earthquake which shook this industrial city early today was accompanied by a roar which sounded as though "all hell had opened up and let loose", Constable Eddie Firn, who was pounding his business district beat when the first tremors were felt, said in an interview.

"First there was a noise which sounded as though a big wind storm was coming up and then the pavement began heaving and sinking under my feet", Firn said. "There was an awful roar which sounded as though all hell had opened up and let loose".

"I was scared stiff and I did not know which way to turn. I was standing in the middle of the road and I went to go one way and a lamp shade toppled from a light post and broke in front of me. I turned to go the other way and a high plate glass window flew out at me. The people began to pour out of their homes...."

On a technical level, only five formal articles have been found as given in references 5 to 9. It should be mentioned that the Cornwall earthquake occurred during war time and that travel and such vital equipment as film were restricted. Dr. Hodgson had 18 exposures available which he used almost exclusively to record movements of cemetery monuments.

The question to ask: can anything still be learned 37 years later which may shed light on the actual ground motion that occurred at Cornwall? Following the pattern of the advanced studies on strong ground motion and source mechanisms now being carried out in California[10], we could compare the structural damage and movement of similar buildings and foundations and the observations of people at home, at work, and in cars, to well-recorded and similar observations that have been made in California. And, on a more complex level, the geology of the earth crust near Cornwall can be modelled, and earthquakes generated mathematically which match the qualitative descriptions.

Figure 1 is a photograph of the west end of Cornwall as it appears today. Parts of the industrial infrastructure you see in the photograph were there in 1944--the Howard Smith Paper Mill (now Domtar) in the foreground, the St. Lawrence Power Station, now demolished, the Roosevelt Bridge (only foundations left), and the seaway canal.

Fig. 1 - View of Site of Howard Smith Paper Mills (now Domtar)

Damage to industrial facilities was not very serious. Some plants stopped work for a few hours and others remained open. At the Howard Smith Paper Mills the new office building was reported to be badly cracked on the inside. The giant smoke stack was split for about nine feet from the top, but was reported to be serviceable. The chlorine plant was closed temporarily when damage was done to some of the cells. The Canadian Industries Limited plant reported that a considerable amount of chemical stoneware was shattered. Brickwork on the corners of the building of CIL was torn loose. The plant was closed for one day to effect repairs. At the St. Lawrence Light, Heat and Power Company, no extensive damage was reported to the Company's equipment or to the buildings. Power did not go off during the event, but a power failure did occur several hours later when a feeder line failed. Apparently the power station "swayed" during the earth tremors and switches were tossed open. A number of insulators were broken as a result of the quake. (It is not reported if the local power station was providing power to the city at the time of the event or if power was fed in from elsewhere). There was no apparent damage to the Roosevelt Bridge (a steel truss structure, now demolished), and in the morning the regular New York Central train bound for Ottawa crossed the bridge on schedule. The bridge was said to have shaken sharply during the tremors and the lengthy spans swayed considerably. The Captain of a boat that passed through the Cornwall locks shortly after the first shock stated that the jar was felt so severely on the boat that the wheel was knocked from his hands. At the time of the shock his boat was in the canal (now abandoned) just west of Cornwall.

Within the town itself, merchandise was thrown from shelves of stores, plate glass windows in stores were broken and an estimated 1000 house chimneys out of 3000 homes toppled to the ground or were severely damaged. The most extensive damage occurred to the 2 major schools, newly built, the Cornwall Collegiate and Vocational School and the Cornwall Public School. At a lecture we gave to the Historical Society[11] we had a rare opportunity to hear first hand the reports of sensations of the motions. The reports received and tape recorded 37 years later were remarkably clear and vivid and compare well with the newspaper account of that day. A sample of the transcript of the tape recording follows:

"HOW MANY PEOPLE WERE HERE IN 1944?" (The answer was 10).

"CAN I HAVE A REACTION FROM ANYONE--FROM THOSE PEOPLE WHO FELT THE EARTHQUAKE? WERE YOU ALL ASLEEP AND AWAKENED, OR WAS ANYONE UP AND AROUND?"

"I was standing between two twin beds, I was just going to get in one when it started to go sideways."

"WAS IT BASICALLY A LATERAL MOTION OR VERTICAL?"

"It was lateral--side to side—out to the street we went and stayed for a couple of hours."

"DID YOU HEAR THE NOISE BEFORE YOU FELT IT OR AFTER?"

"I thought it was a truck hitting my house."

"Our eyes and ears were straining—worn out--for days afterwards, listening, waiting for those sounds that would signal the next earthquake".

"I was never so frightened in my life. I thought I was going to die. I arrived on Monday on the 4:30 train to teach school (girls gym) the next day. That night--I'll never forget it. The girl's gym was destroyed. We didn't get it fixed until January."

Of all the sensations reported, sound was the most vividly remembered--this was reported by those out in the open and within buildings. Persons driving cars during the earthquake reported strange behaviour of their automobiles. One man reported that he thought the four tires had suddenly come off his wheels and he was driving on the rims. As near as can be determined, the first shock occurred at 12:38 a.m. of September 5, 1944, and consisted of four distinct shocks with continued intermittent rumbling for almost an hour. The second shock at 4:32 a.m., the third at 4:53 a.m., the fourth at 7:00 a.m., the fifth a 7:10 a.m. After shocks continued for days and less severe ones for months after.

(b) The Temiskaming Earthquake,[12] November 1, 1935

Just after midnight, Halloween night, an earthquake struck almost directly underneath the town of Temiskaming, Quebec. There was some damage but no casualties. Again, there was no engineering follow-up on this event, although E. A. Hodgson carried out a very thorough field reconnaissance.

This shock alarmed people in Toronto, Ottawa, Montreal, and, for that matter, Cornwall. It was felt in the mines of Kirkland Lake and Sudbury. It caused a landslide on a railway embankment 180 miles distant, it discoloured a local lake.

We were fortunate to interview an eyewitness of this event, Mr. K. J. Mooney, a resident of Temiskaming since 1935. In his words, "It was after midnight. I had just returned to my room (2nd storey of a hotel) when I heard thunder. I was not expecting a storm so I went to the window to look—sure enough, the moon and stars were still visible. Then the shaking started—it felt violent. I could hardly stand--books fell from a high shelf—I could hear people screaming. I rushed to the door and went out into the hallway--the innkeeper and his wife were just coming out of their door". The next day he could see the damage. The chimney of the hotel had broken off at the roof line, windows were broken in shops, at the paper company which was operational at the time, the lights went out, some stock came loose, the most difficulty was encountered with the men trying to turn off valves in the dark to stop the process. Loss of production was limited to one day. There was an operator high up on the cable tower used to transfer logs--he told of severe lateral vibrations. The railway from Temiskaming to Dozois had some problems. Work crews of which Mr. Mooney was a member had to fill cracks in the railroad fill. Past Tee Lake, cracks to a depth of 10 feet were observed perpendicular to the rails at about 100 foot spacing.

(c) The St. Lawrence Earthquake[3]
February 28, 1925

This event caused damage to grain-loading facilities on the banks of the St. Charles River at Quebec City, some 80 miles from the epicentre. In the near field, the damage pattern of brickwork was similar to that reported at Cornwall but perhaps more intense. The damage in terms of dollars was very much less than Cornwall.

The examination of these three historical earthquakes leads us to conclude that the near-field ground motion must have been very similar: the "crisp" damage pattern--cracked plaster, shattered chimneys, limited brick work damage, broken glass, disturbed shelfgoods, and the reports of the residents as to noise, sudden shock, comparing the event to a plane or truck crash on their house--leads us to believe that the near-field ground shaking can be characterized by high peak acceleration, high frequency, and short duration.

FIELD STUDIES OF NEAR-FIELD STRONG GROUND MOTION

In this part of our investigation, we analysed the data of ground motion as recorded in the Strong-Motion Information Retrieval System[13] of the U.S. Geological Survey for the period 1978-1979 and we examined one earthquake event, the El Centro earthquake of October 15, 1979 in detail.

The Strong-Motion Information Retrieval System was developed as part of the Strong-Motion Program operated by the U.S. Geological Survey. Information about earthquakes that have produced significant strong-motion records, the recording sites, the records recovered, and the extent of the analysis that has been performed on the records are available from the system. We requested from the system all the earthquakes recorded for the period 1 January 1978 to 31 December 1979. These data are shown in Table 1.

	event-id	e-mag	e-max-mmi	event-name
1)	13aug78	5.10		Santa Barbara Channel
2)	16mar78			Jenkinsville, SC
3)	27aug78	2.70		Jenkinsville, SC
4)	31aug78			Jenkinsville, SC
5)	27oct78	2.50		Jenkinsville, SC
6)	27oct78b	2.80		Jenkinsville, SC
7)	29nov78	7.80		Oaxaca
8)	00oct77			Southern California
9)	00oct77			Imperial Valley
10)	00nov77			Southern California
11)	00mar78			Hawaii
12)	23jun78			Southern California
13)	00aug78			Southern California
14)	04oct78	5.70		Eastern California
15)	01jan79	4.60		Malibu
16)	12feb79	4.40		Southern California
17)	28feb79	7.70		Southern Alaska
18)	15mar79	5.00		Southern California
19)	15mar79b	5.20		Southern California
20)	15mar79c	5.00		Southern California
21)	22feb79	5.20		Northern California
22)	00aug78			Southern Hawaii
23)	19nov78	4.10		Southern California
24)	01jan79	4.30		Seattle
25)	15oct79	6.40		Imperial Valley
26)	06aug79	5.50		Coyote Lake
27)	26mar78	4.50		northern California
28)	27jan79	5.40		Southern Alaska
29)	13feb79	6.50		Southern Alaska

TABLE 1: EARTHQUAKES RECORDED IN THE USGS STRONG-MOTION INFORMATION RETRIEVAL SYSTEM FOR THE TWO YEARS 1978, 1979 (29 EVENTS).

(A note of caution. This is not necessarily a complete record of all earthquakes that are of interest to earthquake engineers as the data base currently describes only those strong-motion records and stations for which the USGS has primary responsibility.)

The 29 earthquakes produced 170 strong motion records. Sorting these data into records as a function of distance from the epicenter produces Table 2. Reviewing these tables, one can make several significant observations. The Santa Barbara earthquake (M5.1) produced high ground acceleration recording a peak of 0.440 at an epicentral distance of 13 km. The Coyote Lake earthquake (M5.5) produced a peak acceleration of 0.44, at an epicentral distance of 12 km; relatively high accelerations (>0.10) were still recorded at distances between 20 and 30 km. The Imperial Valley earthquake (M6.4) produced anomalously high acceleration values at various distances up to 50 km with the highest value yet recorded, 1.74 g at 27 km.

	r-event-id	r-stn	r-peak-a	r-trans-l
1)	13aug78	5137	0.220	
2)	04oct78	1444	0.260	ABUT
3)	27aug78	2532	0.253	gnd
4)	19nov78	5075	0.110	gnd
5)	06aug79	1445	0.230	gnd
6)	15oct79	5054	0.810	gnd

A) DISTANCE 0.0 TO 10.0 KM

	r-event-id	r-stn	r-peak-a	r-trans-l
1)	13aug78	5093	0.440	gnd
2)	13aug78	885	0.370	gnd
3)	01jan79	5081	0.090	gnd
4)	01jan79	5080	0.060	gnd
5)	12feb79	5044		gnd
6)	12feb79	5047		gnd
7)	19nov78	5074		gnd
8)	19nov78	5076	0.050	gnd
9)	19nov78	5077		gnd
10)	06aug79	1413	0.420	gnd
11)	06aug79	1411	0.440	gnd
12)	06aug79	1410	0.270	gnd
13)	06aug79	1409	0.260	gnd
14)	06aug79	1408	0.130	gnd
15)	15oct79	5053	0.280	gnd
16)	15oct79	5155	0.320	gnd
17)	15oct79	5055	0.310	gnd

B) DISTANCE 10.0 TO 20.0 KM

	r-event-id	r-stn	r-peak-a	r-trans-l
1)	04oct78	1490	0.090	GND
2)	01jan79	5079	0.070	gnd
3)	01jan79	410		gnd
4)	01jan79	638		gnd
5)	01jan79	757	0.060	bsmt
6)	01jan79	657		bsmt
7)	01jan79	657	0.060	10th floor
8)	01jan79	657	0.170	17th floor
9)	06aug79	1251	0.030	gnd
10)	06aug79	1492	0.120	gnd
11)	06aug79	1377	0.120	gnd
12)	06aug79	1422	0.050	gnd
13)	15oct79	5090	0.320	gnd
14)	15oct79	5154	0.270	gnd
15)	15oct79	5057	0.270	gnd
16)	15oct79	955	0.610	gnd
17)	15oct79	952	0.710	gnd
18)	15oct79	942	1.740	
19)	15oct79	5028	0.650	gnd
20)	15oct79	958	0.640	gnd
21)	15oct79	117	0.400	gnd
22)	15oct79	412	0.230	gnd
23)	15oct79	5058	0.380	gnd
24)	15oct79	931	0.150	gnd
25)	15oct79	5165	0.930	gnd
26)	15oct79	5055	0.310	gnd

C) DISTANCE 20.0 TO 30.0 KM

	r-event-id	r-stn	r-peak-a	r-trans-l
1)	04oct78	1325	0.060	gnd
2)	04oct78	1008	0.030	GND
3)	01jan79	410		gnd
4)	01jan79	5108		gnd
5)	01jan79	5108		5th floor
6)	01jan79	5108	0.090	roof
7)	01jan79	949		crest
8)	01jan79	949		downstream
9)	15mar79	5071		gnd
10)	15mar79b	5071		gnd
11)	15mar79b	5072		gnd
12)	15mar79c	5071		gnd
13)	22feb79	1505		abut
14)	06aug79	1422	0.050	gnd
15)	06aug79	1032	0.020	gnd
16)	06aug79	1376	0.040	gnd
17)	15oct79	5054	0.150	gnd
18)	15oct79	5115	0.430	gnd
19)	15oct79	931	0.150	gnd
20)	15oct79	5059	0.150	gnd

D) DISTANCE 30.0 TO 40.0 KM

	r-event-id	r-stn	r-peak-a	r-trans-l
1)	01jan79	892		bsmt
2)	01jan79	892		31st floor
3)	01jan79	892		55th floor
4)	01jan79	655		bsmt
5)	01jan79	655		gnd
6)	01jan79	655		roof
7)	01jan79	288		bsmt
8)	15mar79b	5069		gnd
9)	15mar79b	5070		gnd
10)	01jan79	2164		crest
11)	06aug79	1376	0.040	gnd
12)	06aug79	1506	0.020	gnd
13)	06aug79	1507	0.020	gnd
14)	06aug79	1508	0.010	gnd
15)	06aug79	1460	0.050	gnd
16)	06aug79	1301	0.030	gnd
17)	06aug79	1414	0.100	gnd
18)	15oct79	5060	0.220	gnd
19)	15oct79	5051	0.200	gnd

E) DISTANCE 40.0 TO 50.0 KM

TABLE 2: RECORDS SORTED ACCORDING TO DISTANCE OF EVENT EPICENTER TO RECORDING SITE

We compared the values of Table 2 to the acceleration attenuation equation which has been used in Canada:[14]

$$a_{(g)} = 0.04\, e^{M} R^{-1.4} \qquad 1979 \qquad (1)$$

where M is magnitude and R (km) is the hypocentral distance (usually used with a hypocentral depth of 18 km). Equation 1 is an empirical formula based on data available up to 1979 and is intended to be applicable for epicentral distances up to 100 km.

M	Epicentral Distance (km)		
	5	15	25
5.0	.1	.07	.05
5.5	.16	.12	.08
6.0	.27	.2	.13
6.5	.44	.32	.22

TABLE 3: ACCELERATION VALUES DERIVED FROM EQUATION (1)

Table 3 provides a sample of acceleration values derived from Equation 1. It may be noted that within a distance of 30 km of the epicentre, some measured accelerations in western North America have been a factor of 4 or more greater than would be predicted by Equation 1. We would add, however, that the high acceleration values of the Santa Barbara, Coyote Lake, and Imperial Valley earthquakes caused no fatalities and very little damage.

We reviewed the reconnaissance report written following the Imperial Valley earthquake and carried out a site visit. We were impressed by the similarity of damage and non-damage reports as reported in the El Centro Press[14] and the impressions of local residents compared to the account given in the Cornwall, Ontario press 37 years ago. There is a similarity in felt sensation and structural effects. With due caution, it appears reasonable to transpose the lessons learned from the west coast to the east coast. Never before had so much strong-motion data been gathered from one event, as well as achieving a world record in peak ground acceleration (1.74 g), yet, in the words of an employee of the El Centro newspaper, "It was no big deal".

From the point of view of nuclear power reactor designers, the response of the El Centro Steam Plant was of direct interest. (Fig. 2). This is a 180 MW(e) gas/oil powered electrical power station. The plant is located approximately 3 miles from the earthquake fault. Nearby accelerometers measured

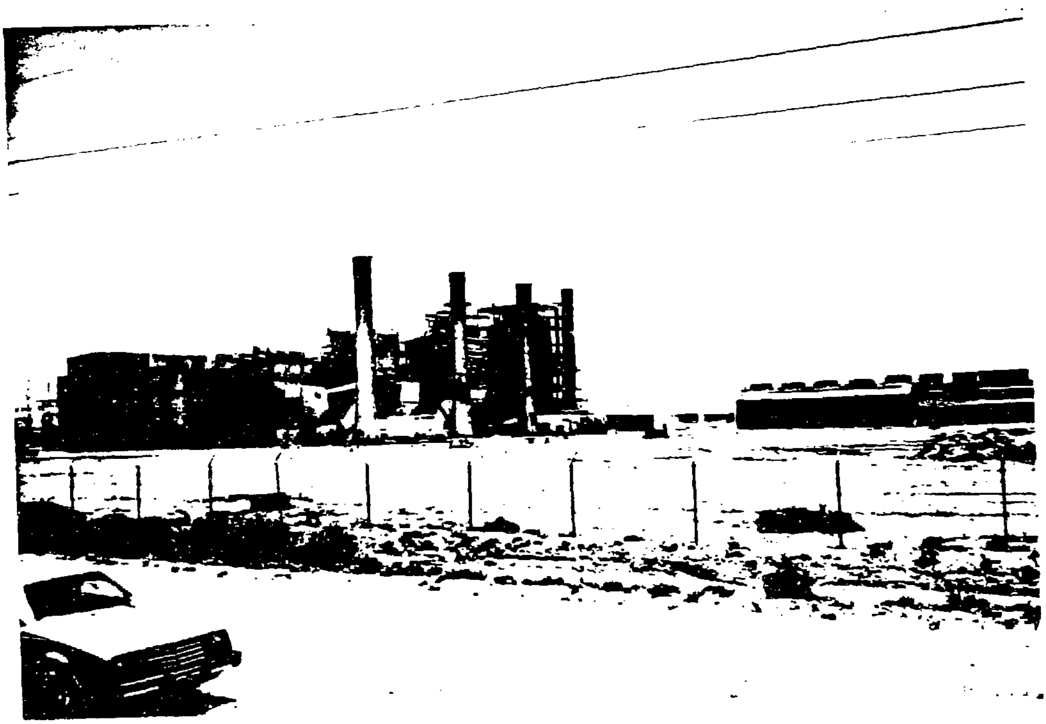

FIGURE 2: EL CENTRO STEAM PLANT

peak accelerations in excess of 0.6 g. The damage within the plant was minimal: two units were running at the time and were tripped off-line during the event because of outside lines "slapping" together. The power plant was designed for a 0.2 g static loading which means that all equipment was designed to resist a lateral force of 20% of its weight applied to the centre of gravity. Major steam lines were flexibly mounted but the designer provided robust "gap" restraints which allowed the pipes their operational thermal movements but limited travel during an extreme shake. Impact forces that may have been generated appeared to have caused no damage. Unit 3 that had been shut down for maintenance did move laterally to impact the floor (gap = 2 inches) of the operating room and damage occurred to the fire-brick due to impact stress waves.

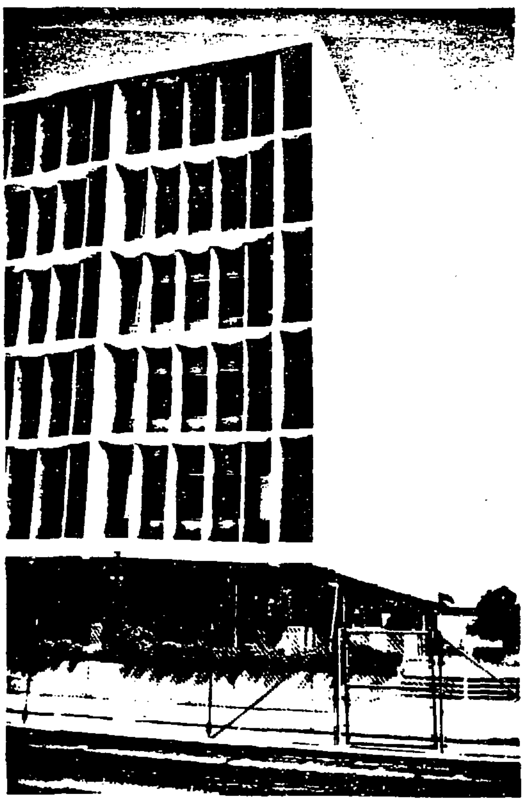

FIGURE 3: IMPERIAL COUNTY SERVICES BUILDING

The only building that suffered serious damage and almost caused a tragedy was the Imperial County Services Building (Fig. 3). Eyewitnesses said that the base of the reinforced concrete columns literally "exploded". This building had been described as "earthquake proof"

NUMERICAL MODELLING

Numerical simulation of seismic waves and resultant ground motion has been employed for the licensing process in the U.S.[1] We have reviewed this technique and have written a finite difference plane strain, elastic code. Figures 4 and 5 are samples of the output of this program. The seismic waves are the results of an initial "rupture" representing an energy release equivalent to 5.45×10^{19} ergs/km slice. Assuming a slide width of 10 km, the energy release is roughly equivalent to a magnitude M6. Our model is very approximate; we show the results here only to indicate that this technique has promise. We are also following with interest the results of Brune[2, 10], who is modelling the rupture process for Diablo Canyon, and we will be monitoring the progress of this technique closely for possible application in future power plants.

SUMMARY

Up to now in Canada we have used relatively low design values of seismic acceleration compared to those used in other parts of the world. This is so because our reactors have been sited in areas of apparently low seismic activity. However, recent evidence would seem to indicate that near-field acceleration may be greater than previously suspected. From evidence obtained from actual structures that have gone through severe earthquakes, we can take some confort in the fact that the conservatism inherent in the design approach and the intrinsic strength of structures and equipment seems to have prevented major damage. However, the evidence is mainly circumstantial so that effort must continue towards gaining a better engineering understanding of the phenomena for

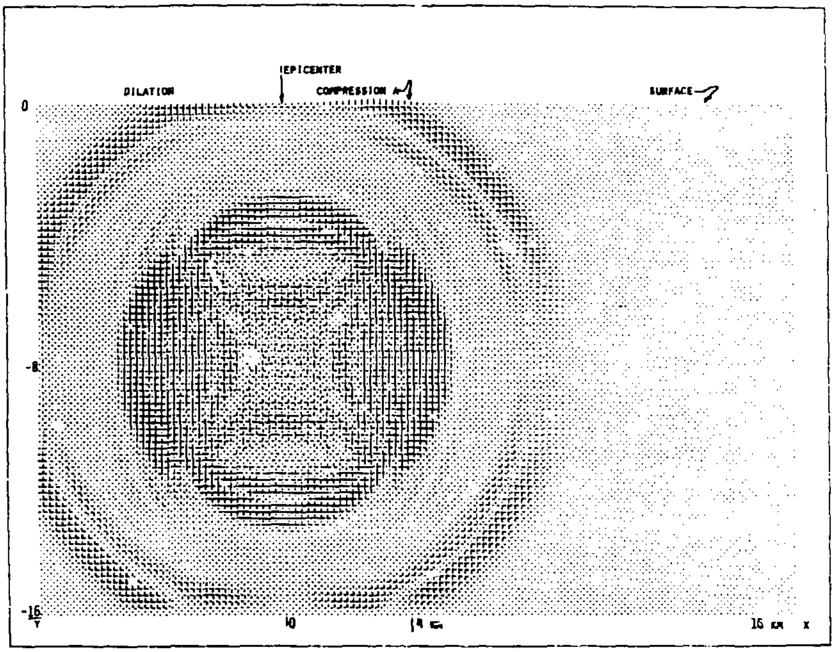

FIGURE 4: SEISMIC WAVES RADIATING OUTWARD DUE TO VERTICAL "RUPTURE" AT HYPOCENTRE (Time = $T_1 + 2\frac{1}{2}$ Sec.)

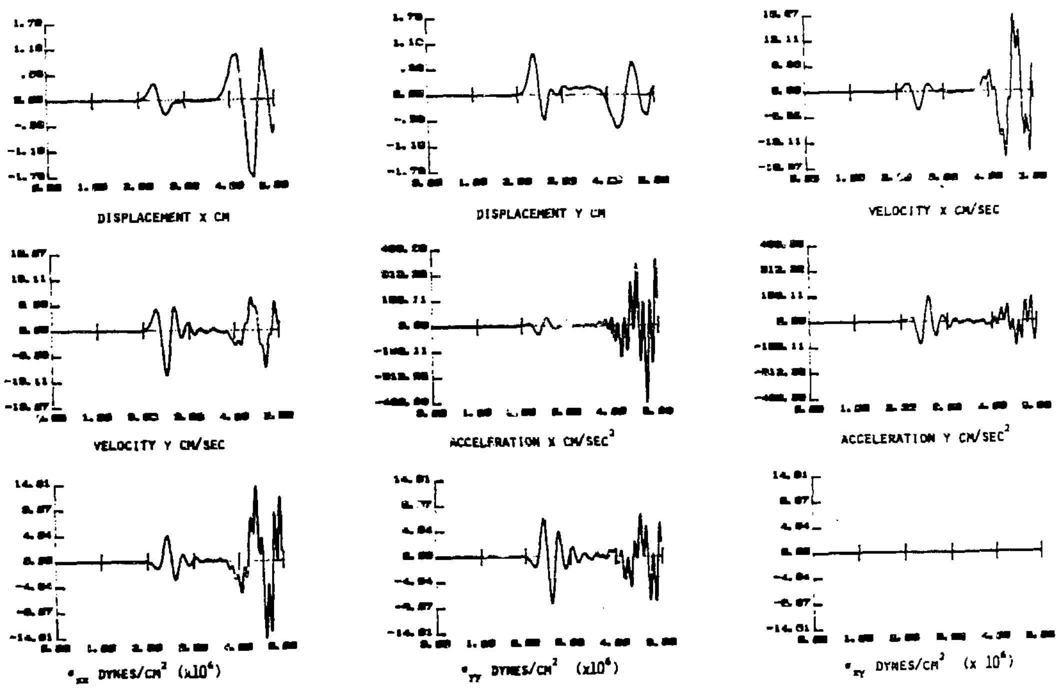

FIGURE 5: GROUND MOTION AT STATION 'A' (INTEGRATION TIME 5 SECONDS)

appropriate design input. In the interim, there is little doubt in our minds that if any of our nuclear power stations exchanged place with the Howard Smith Paper Company in space and time, the nuclear power plant would have come through essentially undamaged.

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