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The Effect of Ground Motion from Nuclear Excavation - Interim
Canal Studies

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THE EFFECT OF GROUND MOTION FROM NUCLEAR EXCAVATION—INTERIM CANAL STUDIES

ABSTRACT

The effect of ground motion due to nuclear excavation of a sea-level canal at two alternative routes, 17A and 25E, are discussed from the aspects of motion prediction and structural response. The importance of the high-rise building problem is stressed because of its complexity. Several damage criteria are summarized for advance planning of excavation and operation. The 1964 shot schedule and the latest revised schedule are included for comparison.

INTRODUCTION

This report is concerned with the effect of ground motion from nuclear excavation of a sea-level canal at two alternative routes, 17A and 25E (Figs. 1 and 2).

The reliability of present methods of predicting ground motion is limited by lack of seismic data induced by nuclear detonation at the range from 200 to 500 km, which represents the distances from Routes 17A and 25E to large cities in Panama and Colombia. Furthermore, applying the ground motion prediction equations derived from experiments at the Nevada Test Site to a new site presents another reliability problem. To solve the range problem, we are trying to collect seismic data in those ranges from various independent agencies, as well as from LRL seismic stations. For the new-site problem, we wish to conduct calibration experiments by which the reliability of motion prediction can be improved, to give more realistic damage estimates.

Since excavation designs always favor the highest yield possible, increasing the yield will increase the damage and safety risk; we wish to find a sensible compromise. High-rise buildings in large cities, such as Panama City and Medellin, present greater risks (as well as financial and political problems) than do dwellings and other low buildings. Tall buildings have long natural periods of vibration that are responsive to long-period ground motion, which does not attenuate much for great distances from the shot point. The situation at Panama City and Medellin is somewhat similar to that of the city of Las Vegas related to NTS (the Nevada Test Site). No damage has yet occurred in Las Vegas, but the maximum yields are far below the considered limit for canal excavation. The motion at the city of Los Angeles from the 1952 Arvin-Tehachapi earthquake seems high enough to consider as an upper bound, because no fatality and structural damage resulted, yet the nonstructural damage in Los Angeles, Long Beach, and Pasadena was estimated at 10 million dollars. The motion in Los Angeles is

Fig. 1. General area map of Route 17A.

Fig. 2. General area map of Route 25E.

equivalent to the effect of a 30-Mt shot 180 km away, which corresponds to Route 17A and Panama City.

The behavior of structures due to ground motion is best described by response spectra, which are, in a sense, influence diagrams for structural response in terms of pseudoabsolute acceleration, pseudorelative velocity, and relative displacement, as functions of either frequency or period at a particular location with a certain percentage of critical damping of the structure. For high-rise buildings, the natural periods generally range from 0.7 to 2.0 sec, so pseudorelative velocity becomes most destructive in this region. For residential buildings, the period is usually less than 0.4 sec, so the pseudoabsolute acceleration will be the most destructive element in this region. For very long-period structures such as towers and skyscrapers, the most destructive element is the relative displacement. Thus, how to predict reliable response spectra for large cities is our main effort in this study.

From the standpoint of safety of persons, prevention of injury is best assured by prevention of collapse of structures. A peak surface particle acceleration of 0.1 g is tentatively set as the structural damage threshold.

The damage estimate for Route 17A is about 108 million dollars, compared to about 254 million dollars on the 1964 schedule. For Route 25E the estimate is about 76 million dollars, compared to about 186 million dollars previously.*

Evacuation plans should be prepared for nearby smaller communities where severe ground motions are expected. For larger cities, selective evacuation will be necessary for some weak spots, in order to raise the yield limit.

MOTION PREDICTIONS

Damage is assessed from response spectra generated from the band-pass filter (BPF) prediction equation of the form $V_b = A_0 R^{B_x} W^{B_y}$, where V_b is the predicted band-pass-filter peak velocity in cm/sec, A_0 is the amplitude constant, B_x is the exponent on distance, B_y is the exponent on yield, R is distance in meters, and W is yield in kt. A_0 , B_x and B_y are calculated from a best-fit curve for data from NTS by ERC (Environmental Research Corporation).¹

It should be noted that these constants have evolved from data recorded at 13 stations for 20 contained detonations at NTS. The equation is applicable in the range of 40 to 180 km. The media of receiving stations have not been taken into account in the regression analysis. However, in the absence of a calibration shot, this general

*Estimates were made by John A. Blume and Associates, San Francisco, California.

equation at present represents the best-response spectra prediction for a new area. Figs. 3, 4, and 5 are response spectra—5% damping at 180 km, 230 km, and 315 km, respectively—for yields of 5, 10, 20, and 30 Mt.

For peak amplitude prediction, we recommended using the latest prediction equations developed by ERC² from the data recorded from 99 underground nuclear events, ranging in yield from about 1 to 1,000 kt and recorded at more than 500 different stations with the range from less than 1 to approximately 600 km. Many of the damage criteria currently in use, especially for planning purposes, are based on the anticipated peak amplitude. Some of the damage criteria derived by various investigators from their observations, experience, and judgment, are summarized in the conclusion of this UCIR.

The prediction equations are divided into three categories according to station media. Figures 6, 7, and 8 show peak surface accelerations of particles versus range for yields from 100 kt to 30 Mt. Because of the variation by both exponents on yield and range, it is interesting to note that three different media give the results shown in Table 1. It can be seen that at 1 km, hard rock gives the higher acceleration; at 10 km, three station media produce accelerations of approximately equal magnitude; and at 100 km, alluvium has the higher acceleration.

Table 1. Peak particle surface acceleration, g, for alluvium, hard rock, and total.

Yield	Range, km								
	Alluvium			Hard rock			Total		
	1	10	100	1	10	100	1	10	100
100 kt	1.59	0.07	0.0030	3.20	0.07	0.0014	1.80	0.07	0.0025
500 kt	4.34	0.19	0.0083	9.19	0.19	0.0040	4.82	0.18	0.0066
1 Mt	6.69	0.29	0.0128	14.49	0.30	0.0063	7.35	0.27	0.0102
5 Mt	18.26	0.80	0.0348	41.64	0.87	0.0182	19.62	0.73	0.0271
10 Mt	28.15	1.23	0.0536	65.61	1.37	0.0286	29.95	1.11	0.0413
20 Mt	43.38	1.89	0.0827	103.40	2.16	0.0451	45.71	1.70	0.0631
30 Mt	55.86	2.44	0.1065	134.90	2.82	0.0589	58.53	2.18	0.0808

Figure 9 shows some of the factors affecting the signature of the ground motion as it is registered by the receiving station:

Source—The media surrounding the shot point influence the efficiency with which seismic energy is coupled from a nuclear explosion. In general, the more competent the material, the more energy will be coupled into the seismic signal. Other factors of importance in the shot media are porosity, amount of water present, and perhaps depth of burial.

Transmission path—The geology of the path the seismic signal follows influences the character of the signal received. The earth has been compared to a band-pass

Fig. 3. Response spectra at a radius of 180 km. The cities concerned are Panama City (Route 17A) and Quidbo (Route 25E); 5% damping.

Fig. 4. Response spectra at 230 km. The cities concerned are Monteria (Route 17A, actual distance 220 km), Colon (Route 17A, and Medellin (Route 25E); 5% damping.

Fig. 5. Response spectra at 315 km. The cities concerned are Panama City (Route 25E, actual distance 300 km), Cartagena (Route 17A, actual distance 300 km), Manizales (Route 25E), and Pereira (Route 25E, actual distance 320 km); 5% damping.

Fig. 6. Range versus peak surface acceleration of particles; station media; total.

Fig. 7. Range versus peak surface acceleration of particles; station media: alluvium.

Fig. 8. Range versus peak surface acceleration of particles; station media: hard rock.

Fig. 9. Concept of predicting ground motion.

filter with attenuation of motion varying directly with frequency. In addition, the presence of layers might provide a channel for transmitting certain frequencies at lesser attenuation rates. The effect of reflection and refraction at boundaries further complicates the problem. Figure 10 shows the variance of peak particle motions as a function of azimuth;³ the differences can be explained partly by reference to the transmission path.

Receiving-site geology—Perhaps the greatest factor affecting both the frequency content and the amplitude of a seismic signal is the local geology at the receiving site. In general, amplitudes of ground motion are enhanced by a layer of alluvium. The exact amplification is not known; presumably the soil layer tends to act as a dynamic system amplifying those frequencies that are near the resonance of the modes of vibration and perhaps are damping other frequencies out. The studies at NTS from nuclear tests have developed stations with relatively constant differences from predicted values. These differences have been accounted for with a station factor correction.

Figure 11 shows the effect of the soil layer at the Tonapha Motel Station. The dashed line represents a spectrum envelope scaled from a low-yield event to a larger yield by single-station regression analysis method; the solid line represents a spectrum predicted for the larger yield as a function of yield and distance by using band-pass-filter prediction equations; the dot-dashed line represents the actual, measured motion at that receiving station. This figure clearly shows the effect of local geology and the usefulness of scaling from a calibration shot.

Building response—The amount of damage that a building receiving ground motion undergoes is going to be determined by the amplitude and frequency of the ground motion, as well as by the dynamic characteristics of the structure. If the resonant frequency of the structure is similar or equal to a predominant frequency in the ground motion signal, the building will undergo sympathetic vibrations and the motion will be amplified, perhaps to the extent of causing damage.

Typical structures range from the one-story adobe and light frame construction in small villages to the modern reinforced concrete frame, high-rise building in the larger cities. There is a large variety of types of construction in the former group,⁴ as shown in Figs. 12 through 19.*

Adobe (Fig. 12)—This type of construction has little resistance to lateral forces.

Tapia (Fig. 13)—Easy construction and economy make this type of house very popular in the rural areas. Tapia houses provide good insulation, but little strength to withstand lateral or dynamic loading.

* Pictures of buildings are courtesy of John A. Blume and Associates.

Fig. 10. Azimuthal distribution for the Salmon Event, with an isoseismal plot showing vector sums of peak horizontal acceleration.

Fig. 11. Response spectra plotted at the Tonopah Motel station. Damping ratio (β) = 0.05.

Fig. 13. Typical tapia residence: Betulia, Colombia.

Fig. 12. Typical adobe residence: Azuero Peninsula, Panama.

Fig. 14. Typical bahareque residence.

Fig. 15. Typical guadua residence: Manizales, Colombia.

Fig. 16. Typical bohio residence, constructed with concrete blocks.

Fig. 17. Typical wood-framed residence: Panama.

Fig. 18. Typical three- and four-story reinforced-concrete apartment house: Colon, Panama.

Fig. 19. Typical high-rise building: Panama City.

Bahareque (Fig. 14)—This type of house is common among the peasants. The wood-pole frame construction resists lateral forces, but inadequate connections and heavy tiled roofing weaken the resistance.

Guadua (Fig. 15)—Guadua is a species of bamboo that grows like a tree; when cut and split, it can be opened out into fine elastic boards. Houses built of such reeds yield easily to vibrations and so are considered comparatively safe, except when heavy clay-tile roofing and mud-plastered walls are used.

Bohio (Fig. 16)—These houses are constructed similarly to the adobe and bahareque, except for the use of concrete block, clay tile, and stucco. Because of the material weight and lack of good construction practices, this type of structure is very susceptible to damage from ground motion.

Wood (Fig. 17)—Wooden structures of up to four stories resist ground motion very well, if joints are securely connected and lightweight roofing material is used.

Three- and four-story construction of reinforced concrete (Fig. 18)—Structures in this size category are considered in the transition zone between one- and two-story light frame construction and multistory structures. Because of primitive craftsmanship, unskilled labor, and lack of quality control and building-code enforcement, the resultant structure is structurally unsound.

Multistory construction (Fig. 19)—Most high-rise buildings in Latin-American countries have reinforced concrete frames with brick, block, or hollow clay-tile filler walls. The masonry filler walls generally are not reinforced, so the strength of the structure is provided by a rigid frame and floor system.

The structural response of low-story rigid buildings and high-rise buildings is basically different. The former response usually can be considered a one-mass system, i. e., single degree of freedom, while the latter will have several modes of vibration, and consequently its response to ground motion will be much more complicated than that of one-mass systems. It is also important to recognize that the higher-frequency components of the ground motion attenuate with distance more rapidly than the lower-frequency components. The consequence of this phenomenon is that low, stiff buildings close to the source would suffer more damage than tall, flexible buildings. On the contrary, for larger yield and greater distance, high-rise buildings with long periods of vibration would be more susceptible to damage than low, stiff buildings.

TOTAL DAMAGE ESTIMATE

The source of estimates for the seismic damage from nuclear excavation for a canal is John A. Blume and Associates, through their Spectral Matrix theory. This program lists all the villages and towns in the excavation areas. The response

envelopes predicted by ERC as a function of yield and distance are computed for each location; and the amount of damage is calculated from the motion-demand and building-capacity statistical probabilities, by use of a "Monte Carlo" technique. The building-capacity parameter is from Blume and is a product of experience and engineering judgment.⁴

As no significant damage has been caused by underground nuclear testing, all the information concerning motion-induced structural damage is a result of earthquake experience. The maximum Las Vegas ground motion from nuclear events to date is less than 0.01 g. The maximum relative spectral response, assuming 5% of critical damping, is 3 cm/sec in the period of 1 to 2 sec. The maximum pseudoabsolute acceleration recorded at the Mint Hotel station, from the Benham event, is 0.08 g transverse and 0.035 g radial; both occurred at the period of 0.05 sec.⁵ The relative effect of response envelopes generated by earthquake versus those resulting from nuclear detonations is unknown, but indications are that earthquakes are more damaging for similar motions and envelopes. We therefore propose that the damage factors chosen to evolve damage predictions are probably conservative, and that additional experience, notably motion-induced damage resulting from nuclear detonations, will result in more precise damage factors and smaller standards of deviation, which will undoubtedly lower the damage prediction.

Table 2 presents the mean values of the accumulation of damage for Route 17A with the revised detonation schedule and the previous schedule,* which are given in Appendix A. The 1969 estimate for Route 17A is 108.376 million dollars, reduced from the 1964 estimate of 254.164 million dollars, and the corresponding values for Route 25E are 75.757 million dollars versus 186.314 million dollars (Table 3).

ESTIMATED STRUCTURAL DAMAGE TO RESIDENCES

Alternative estimates of damage are based on the relationship of probable damage complaints and pseudoabsolute acceleration. Nadolski examined architectural damage to residential structures caused by seismic disturbances and concluded that a plot of damage complaints versus the pseudoabsolute acceleration was an effective damage-prediction criterion.⁶ Figure 20 is an up-to-date version of this plot, in which many data points from recent experiments have been added. By using this plot combined with the response predictions by ERC,⁷ we found the total number of complaints. (The detailed calculations are included in Appendix B.) It should be noted that Nadolski's approach deals exclusively with the residential type of buildings.

*The 1969 shot schedule was issued on 11 March 1969 and was revised on 3 April 1969. The largest yield in the revised schedule was decreased from 14.5 Mt to 13.5 Mt, while the total combined yield was increased from 120 Mt to 129 Mt. The 1969 damage estimate is based on the 3 April version. See Appendix A.

Fig. 20. Plot of the relationship of damage complaints and claims to pseudoabsolute acceleration, for a variety of events. Damping ratio (β) = 0.10.

Table 2. Predicted cumulative damage costs, Route 17A, in millions of U. S. dollars.

Panama				Colombia			
Previous schedule (1964), shot	Estimated damage (1964), mean	Present schedule (April 1969), shot	Estimated damage (April 1969), mean	Previous schedule (1964), shot	Estimated damage (1964), mean	Present schedule (April 1969), shot	Estimated damage (April 1969), mean
1	19.575	1	9.113	1	6.469	1	0.423
2	40.742	2	14.003	2	13.323	2	0.833
3	58.330	3	17.547	3	19.005	3	1.339
4	82.705	4	23.036	4	30.607	4	2.199
5	92.863	5	27.426	5	33.002	5	2.933
6	100.346	6	32.952	6	34.758	6	3.794
7	103.992	7	36.424	7	35.524	7	4.425
8	112.795	8	40.359	8	37.746	8	5.245
9	117.901	9	43.930	9	38.787	9	5.909
10	124.263	10	45.908	10	41.809	10	6.376
11	126.288	11	48.963	11	43.490	11	7.092
12	131.205	12	50.836	12	46.272	12	7.503
13	142.432	13	52.243	13	53.813	13	8.178
14	149.662	14	54.406	14	56.022	14	8.754
15	154.818	15	57.831	15	59.248	15	9.726
16	162.463	16	61.040	16	61.608	16	10.477
17	164.772	17	63.858	17	62.007	17	11.102
18	168.428	18	66.583	18	63.066	18	12.092
19	173.100	19	69.352	19	64.810	19	13.177
20	176.799	20	79.307	20	66.433	20	17.715
21	180.195	21	81.908	21	67.548	21	18.435
22	184.520	22	83.496	22	69.644	22	18.968
		23	84.626			23	19.522
		24	86.020			24	20.237
		25	87.574			25	20.802

Table 3. Predicted cumulative damage costs, Route 25E, in millions of U. S. dollars.^a

Panama				Colombia			
Previous Schedule (1964), shot	Estimated damage (1964), mean	Present schedule (April 1969), shot	Estimated damage (April 1969), mean	Previous schedule (1964), shot	Estimated damage (1964), mean	Present schedule (April 1969), shot	Estimated damage (April 1969), mean
1	5.127	1	0.853	1	7.503	1	1.044
2	14.557	2	2.362	2	22.125	2	3.256
3	21.323	3	2.963	3	33.345	3	4.375
4	23.789	4	4.272	4	37.581	4	6.597
5	30.648	5	5.441	5	48.958	5	8.480
6	33.997	6	7.721	6	57.515	6	12.184
7	36.912	7	11.628	7	65.689	7	20.661
8	37.534	8	13.389	8	67.776	8	24.038
9	39.538	9	14.296	9	71.882	9	26.150
10	50.629	10	15.061	10	93.810	10	28.221
11	53.197	11	15.666	11	98.489	11	29.442
12	56.033	12	16.364	12	105.510	12	30.738
13	57.533	13	17.713	13	109.204	13	32.752
14	61.017	14	18.481	14	119.135	14	34.723
15	62.485	15	19.418	15	123.829	15	36.712
		16	20.269			16	38.778
		17	21.072			17	40.451
		18	21.786			18	42.277
		19	22.591			19	43.989
		20	23.235			20	45.711
		21	23.946			21	47.465
		22	24.621			22	48.779
		23	25.088			23	50.669

^aThe 1964 schedule is for Route 25A; the April 1969 schedule is for Route 25E.

According to structural response characteristics, buildings may be divided into at least two major categories: the low-frequency, high-rise buildings; and the relatively high-frequency, one- to four-story rigid structures, which we consider as residential structures. The residential damage predictions should not be used for predictions of total damage, as they might present too optimistic a view, especially for large cities containing many large commercial buildings.

Tables 4 and 5 are summaries of residential complaints estimated for Routes 17A and 25E, respectively. The total of residential complaints from Route 17A is about 22,300 and, from Route 25E, about 24,000. Total damage in dollar values may be obtained by assuming an average cost per complaint and multiplying the total number of complaints by this unit cost (see Table B-3, Appendix B). We separated the complaints for Colombia and Panama, and we varied the cost of claims according to type of structure, size of town, and local construction and repair cost.

The damage estimates for the rural areas present a problem for the time being. We are searching for more dependable data on population distribution. Therefore, the percentage of complaints for the rural area are tentative and subject to revision when appropriate data are available.

ESTIMATED STRUCTURAL DAMAGE TO HIGH-RISE BUILDINGS

The possibility of severe structural damage to high-rise buildings because of induced ground motion from the nuclear detonations will be instrumental in determining the allowable yields for canal construction. Experience with this phenomenon is very limited, primarily to Las Vegas buildings subjected to motions from high-yield nuclear tests at NTS. At this time, no identifiable damage has been observed.

We assume that manifestations of damage will appear prior to severe structural damage that would endanger the public or reduce the structural integrity of the buildings. Until damage to high-rise buildings from nuclear-induced ground motions is in evidence in Las Vegas, the present data can best be used as an indication of the zero point of the demand-capacity overlap of the structures studied. Translating this information to the effects at a different site, especially one with less stringent building codes, requires experience and engineering judgment. The opinion of John A. Blume Associates⁴ is that, in general, the integrity of high-rise structures in the area of interest near the Panama Canal Route is less than that of the buildings in Las Vegas. As experience in Las Vegas mounts with greater yields and greater ground motions, estimates of the structural capacities of the affected high-rise buildings will become more reliable as we approach the actual capacities. While there are differences in the seismic signals generated by earthquakes and by nuclear detonations, the characteristics of the ground motion are similar, notably in the generation of the response envelope, which is the characteristic used to predict damage for the canal excavation.

Table 4. Residential complaint estimate - Route 17A.

Group	City	Distance (km)	Structures ≤ 4 stories	PSAA ^a (12.5 Mt) (cm/sec ²)	% complaints (total)	Total No. complaints
I	Panama City	180	70,000	31.8	9.78	6,850
	Monteria	220	8,340	24.9	5.44	454
	Colon	230	10,000	24.9	5.44	544
	Cartagena	300	31,240	23.4	3.56	1,113
	Rural	115-285	35,100		5.5	1,920
	Total					10,881
II	Medellin	385	106,603	19.9	2.78	2,965
	Barranquilla	405	68,500	18.3	2.23	1,525
	Rural	285-460	62,330		3.8	2,278
	Total					6,768
III	Manizales	495	24,120	16.0	1.46	352
	Bucaramanga	530	37,000	16.0	1.46	540
	Cali	625	89,100	14.4	1.02	908
	Bogota	630	179,690	14.4	1.02	1,830
	Rural	460-560	68,300		1.5	997
	Total					4,627
Overall total complaints						22,276

^aPseudoabsolute acceleration spectrum.

Table 5. Residential complaint estimate - Route 25E.

Group	City	Distance (km)	Structures ≤ 4 stories	PSAA ^a (12.5 Mt) (cm/sec ²)	% complaints (total)	Total No. complaints
I	Medellin	230	106,603	23.4	5.5	5,820
	Monteria	260	8,340	22.4	4.9	405
	Panama City	300	70,000	22.0	3.6	2,516
	Manizales	315	24,121	22.0	3.6	870
	Rural	155-285	34,930		6.2	2,173
	Total					11,784
II	Colon	360	10,000	18.7	2.7	272
	Ibaque	385	16,670	18.7	2.7	453
	Cali	420	89,100	17.3	2.2	2,005
	Cartagena	435	31,240	17.3	2.2	698
	Rural	285-460	110,000		2.5	2,881
	Total					6,309
III	Bogota	465	179,690	15.0	1.4	2,565
	Bucaramanga	480	37,000	15.0	1.4	528
	Barranquilla	525	68,500	15.0	1.4	980
	Rural	460-560	128,300		1.4	1,795
	Total					5,868
Overall total complaints						23,961

^aPseudoabsolute acceleration spectrum.

The total seismic energy released in a major earthquake is usually much greater than that resulting from nuclear detonations; for similar relative velocity envelopes, therefore, earthquake-generated envelopes would cause more damage to structures.

Figure 21 shows the response envelope for Los Angeles for the Tehachapi earthquake of 1952. It is presented because the damage occurring to high-rise structures in Los Angeles was significant, but not structural in nature.^{8,9} No loss of life, the parameter of greatest importance in yield limitations, resulted from the damage to buildings in Los Angeles.

The applicability of building damage in Los Angeles, with its stricter building codes and more rigid inspections than apply in the prospective canal areas, is open to question; however, many of the buildings damaged were constructed prior to 1920, when codes and requirements were not as specific or as strict as they are today. We propose that the response envelope of the 1952 earthquake in Los Angeles provides a viable indication of the strength of structures; and it is reasonable to expect damage, even to the weaker buildings in the canal area, to be less than total. It must be recognized that a few specific structures may exist that would represent a greater susceptibility to seismic motions and that "hot spots" or areas of unusual seismic amplification might cause problems, but these cases would probably be discovered in a well-designed calibration series of detonations and further defined as work progressed. The shot schedules indicate that several of the lower-magnitude salvos will precede the largest shot, so that these anomalies can be located and specific buildings can be evacuated or even razed if deemed necessary.

Just as there is no assurance the experience with Las Vegas high-rise buildings will identify an absolute threshold of damage to them, there is an even greater lack of certainty of the capacity of the structures in Los Angeles and Panama or Columbia. One can be certain that damage will be greater in the weaker buildings, but their capacity to resist structural damage can only be determined by more study and analysis of specific buildings. There is a notable lack of data on South and Latin American buildings damaged in earthquakes with recorded motions, and the response envelope generated for Bogota from the Neiva earthquake in February 1967 (Fig. 22*) resulted in only slight damage to high-rise structures, thus reinforcing the judgment of a lower threshold but not indicating a limiting motion envelope for structural damage.

EVACUATION

Tentative criteria for evacuation can be established only as functions of peak particle motion. On the basis of the information gained from earthquakes, notably the

*Figure 22 courtesy of John A. Blume and Associates.

Fig. 21. Response spectra, comparing the Los Angeles earthquake of 1952, 30 Mt at 180 km, and 5 Mt at 180 km; 5% damping.

Fig. 22. Earthquake response spectra, compared with response spectrum for the Boxcar Event; 5% damping.

Modified Mercalli Intensity Scale, a preliminary assessment of intolerable motions without general evacuation would be approximately 0.10 to 0.15 g. This can be compared to an MMI of between VII and VIII, which is described as severely damaging to weak masonry and adobe dwellings.¹⁰ While it is true that many of the native huts are very flexible and therefore resistant to damage from ground motions, the use of tile roofs creates great danger to human lives.

The procedures for public safety would not necessarily decree total evacuation; it would be sufficient to ensure that people be removed from the more susceptible structures, to eliminate the possibility of injury from falling ceilings or collapsing roofing materials. A cost analysis should be run to decide the question of total or partial evacuation of the affected villages.

A more detailed procedure for evaluating the need for evacuation can be obtained from the Spectral Matrix method of damage prediction.¹¹ Blume suggests evacuation when

1. Estimated 5% PSAA values exceed 0.1 g;
2. Estimated average damage factor (F_{av}) exceeds 0.001 in a given area (where F is the ratio of damage cost to the total value of buildings in a given area);
3. In Spectral Matrix Analysis, 1 or more simulations (out of 10) have F values exceeding 0.20;
4. Upper level response in a high-rise building exceeds
 - (a) 0.05 g or
 - (b) 4 times the design base shear coefficient; or
5. A high-rise building has a design base shear (at code unit stresses) less than the predicted 5% spectral response acceleration.

This type of information is readily available from the present computer code used by Blume.

The above criteria are also preliminary and should be modified in accordance with information learned from experience in Las Vegas and especially from a calibration series near the proposed canal route. Because the damage factors for given motion are predicated on earthquake experience and engineering judgment, it is reasonable to expect them to be conservative. To date, there has not been any serious structural damage associated with ground motions induced from nuclear explosions and the advent of such damage will give a much greater insight into the relevancy of the chosen evacuation criteria. It should be emphasized that the evacuation criteria listed above will probably be more inclusive than the proposed value of 0.1 g, and that the statistical nature of the problem requires significant experience above the damage threshold values of 0.025 g now being experienced in Nevada, to provide a better source of data for re-evaluating the evacuation criteria.

CONCLUSIONS

The aim of this report is to study the ground motion effects on structures and the possible consequences in terms of damage estimates and safety of persons. In order to improve the reliability of ground motion predictions and damage estimates, calibration shots or shots with various, increasing yields are extremely desirable.

The following summary of ground motion criteria may be useful:

0.5 g (peak acceleration)—no deaths as a consequence of earthquake damage to structures;⁴ this value may be used as an upper bound of safety of persons.

0.3 g—from a structural standpoint, this value is considered tolerable motion for runways, bordered facilities, metal buildings, control-point area, etc.¹²

0.1 g—tentative evacuation criteria for native construction in the villages of Central America;¹³ this value and 10 cm/sec velocity are commonly accepted damage criteria for residential houses.

0.02 g—lower-bound damage threshold for low-rise structures in populated areas, such as Panama City and Medellin;⁴ this is also the significant cracking threshold for architectural damage.¹⁴

0.004 g—damage threshold for first cracking.¹⁴

Figure 23 is plotted by calculating range versus yield for the above criteria. It should be noted that the latest ERC regression equations include the station media of "total," which logically should be used for unknown stations. However, Table 1 indicates that the alluvium equation gives higher accelerations for larger distance and yield. Because our interest is in megaton yields and populated cities located far from the source, the alluvium equation was used for Fig. 23.

One point should be specially stressed: high-rise buildings. The prognosis for high-rise structures cannot be adequately presented by a statistical approach. As previously discussed, the uncertainty of ground motion prediction and the complexity of high-rise building structural response are two basic problems. Besides, the structural analysis of each high-rise building is extremely difficult and may be misleading, so that even if ground motion could be predicted with reasonable accuracy, the prediction of damage threshold would still be uncertain. Furthermore, as the damage progresses, the dynamic characteristics of the structure might be changed to an extent that the dynamic response calculations are no longer valid. It is also difficult to distinguish between architectural and structural damage, because components designed for architectural purposes, such as filler walls and partitions, may actually be carrying part of the load and adversely become structural members; the failure of these members due to ground excitation may significantly affect the structural integrity. Therefore, much more is to be learned about the nature, response, and damage of structures, and about the behavior and interaction of nonstructural elements subjected to ground motion.

Fig. 23. Range versus yield for various ground motion criteria; station media: alluvium.

The damage estimate is based on the structural response calculations, which are obtained by applying the Spectral Matrix method; in turn, ground motion predictions by ERC are used as part of the input for the Spectral Matrix calculations. Consequently, the results are subjected to the compound inaccuracies rising from the unreliability of ground motion predictions for a new site and the unreliability of probable structural responses. In conclusion, it is clear that any improving of technology on either or both aspects certainly would help to reduce the range of values in the ground motion predictions and to increase our understanding of ground motion effects and structural behavior.

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APPENDIX A
PREVIOUS AND REVISED DETONATION SCHEDULES

Table A-1. Detonation schedule for interoceanic sea-level canal on Route 17A (1964).^a

Stations		Detonation No.	No. of explosives	Total yield (Mt)
From	To			
35 + 00	174 + 79	11	20	8.4
187 + 62	250 + 96	1	6	16.0
267 + 75	321 + 91	13	4	22.0
334 + 73	392 + 69	4	4	30.0
409 + 48	451 + 91	15	4	14.0
468 + 70	519 + 06	3	4	17.0
531 + 88	580 + 80	12	5	12.0
597 + 59	647 + 96	2	4	20.0
664 + 74	734 + 58	20	7	10.0
745 + 04	836 + 17	10	10	14.0
852 + 96	947 + 94	19	10	10.5
950 + 00	1200 + 60	9	50	7.6
1212 + 50	1473 + 10	18	50	8.8
1488 + 60	1700 + 60	8	32	11.0
1712 + 50	1945 + 30	17	50	5.2
1954 + 18	2042 + 69	7	13	5.8
2053 + 14	2188 + 41	16	15	12.0
2196 + 94	2245 + 80	6	6	9.5
2262 + 59	2353 + 83	14	10	11.5
2362 + 36	2544 + 04	5	31	11.6
950 + 00	1421 + 90	21	50	7.5
1433 + 80	<u>1945 + 30</u>	<u>22</u>	<u>50</u>	<u>10.4</u>
Total	255,904 ft (48.5 mi)	22	435	274.8

^aNuclear Excavation Design (Preliminary)—Route 17, U. S. Army Engineer Nuclear Cratering Group, IOCS Memorandum NCG-1200-17-31, Ser. NCG-25 (December 1967).

Table A-2. Detonation schedule for interoceanic sea-level canal on Route 17A
(March 1969).^a

Salvo No.	Number of explosives	Total yield (Mt)
1	5	2.5
2	7	4.0
3	10	5.0
4	9	5.0
5	6	4.5
6	10	5.0
7	6	5.0
8	7	5.0
9	10	5.0
10	5	3.0
11	5	5.0
12	5	4.0
13	8	5.0
14	6	4.5
15	5	5.5
16	5	6.0
17	7	4.5
18	5	5.5
19	5	6.0
20	5	14.5
21	5	5.5
22	6	4.5
23	7	5.0
24	9	4.5
Total	158	124.0

^aJ. Danielson, Nuclear Detonation Schedule for Interoceanic Sea-Level Canal on Route 17-A, LRL Internal Memorandum UOPKC 69-15 (March 11, 1969).

Table A-3. Revised detonation schedule for interoceanic sea-level canal on Route 17A (April 1969).^a

Stations		Salvo No.	No. of explosives	Total yield (Mt)
From	To			
0 + 00	62 + 00	1	6	3.5
62 + 00	138 + 50	2	8	4.0
138 + 50	219 + 00	3	8	4.0
219 + 00	301 + 50	4	9	5.0
301 + 50	356 + 50	5	6	4.5
356 + 50	446 + 50	6	10	5.0
446 + 50	497 + 50	7	6	5.0
497 + 50	562 + 50	8	7	5.0
562 + 50	650 + 00	9	10	5.0
(Conventional excavation for clay-shale section)				
1665 + 00	1721 + 00	10	6	4.0
1721 + 00	1772 + 00	11	5	5.0
1772 + 00	1825 + 50	12	6	4.0
1825 + 50	1879 + 00	13	6	4.0
1879 + 00	1929 + 50	14	6	4.5
1929 + 50	1976 + 50	15	5	5.5
1976 + 50	2023 + 50	16	5	6.0
2023 + 50	2090 + 00	17	7	5.0
2090 + 00	2133 + 00	18	5	5.5
2133 + 00	2183 + 50	19	5	6.0
2183 + 50	2232 + 50	20	5	13.5
2232 + 50	2279 + 50	21	5	5.5
2279 + 50	2332 + 50	22	6	5.0
2332 + 50	2397 + 50	23	7	5.0
2397 + 50	2497 + 50	24	10	5.0
2497 + 50	2582 + 00	25	9	4.5
Total		25	168	129.0

^aJ. Danielson, Revised Nuclear Detonation Schedule for Interoceanic Sea-Level Canal on Route 17-A, LRL Internal Memorandum, UOPKC 69-25 (April 3, 1969).

Table A-4. Revised detonation schedule for interoceanic sea-level canal on Route 17A (August 21, 1969).^a

Stations		Detonation identification	No. of explosives	Total yield (Mt)
From	To			
1432 + 00	1567 + 50	A	16	5.0
1575 + 70	1706 + 05	B	16	4.5
1714 + 10	1752 + 00	C	5	5.5
1762 + 30	1830 + 55	D	13	4.3
1837 + 70	1912 + 65	E	12	5.2
1918 + 35	2020 + 45	F	15	5.0
3065 + 00	3139 + 75	G*	13	5.9
3151 + 20	3209 + 10	H	9	4.9
3217 + 15	3299 + 15	I	9	5.1
3307 + 20	3360 + 40	J	8	5.6
3373 + 30	3407 + 65	K	5	5.2
3417 + 95	3471 + 55	L	8	5.0
3479 + 60	3527 + 55	M	7	5.8
3540 + 45	3591 + 75	N	7	7.1
3602 + 05	3645 + 60	O	5	11.0
3654 + 75	3702 + 95	P	7	4.9
3712 + 30	3762 + 35	Q	7	6.5
3770 + 40	3835 + 70	R	7	4.9
3842 + 85	3949 + 45	S	14	2.9
Total	147,290 ft (27.9 mi)		173	104.2

* Detonation G includes five explosives for T-row interception of the Chucunaque River

River Diversion Channels

7 + 50	211 + 20	U	19	7.3
0 + 00	61 + 50	T	7	2.2
0 + 00	99 + 65	Z	11	2.9
0 + 00	60 + 90	Y	8	0.8
0 + 00	78 + 30	X	10	1.4
0 + 00	69 + 60	W	9	1.0
—	—	V	1	1.0
Total			65	16.6

^a This detonation program was agreed upon by LRL and the Nuclear Cratering Group (NCG). It will be incorporated in Appendices 12 and 13 of Annex V-Engineering Feasibility Study, Interoceanic Canal Studies and will be used as the basis for that entire study.

Table A-5. Detonation schedule for interoceanic sea-level canal on Route 25A (1964).^a

Stations		Detonation No.	No. of explosives	Total yield (Mt)
From	To			
4175 + 75	4202 + 78	8	7	5.0
4213 + 23	4291 + 16	15	8	11.0
4303 + 98	4359 + 24	7	5	13.0
4372 + 06	4414 + 49	14	4	14.0
4431 + 28	4496 + 99	6	6	12.5
4505 + 52	4571 + 06	13	7	9.5
4583 + 88	4634 + 25	5	4	17.0
4647 + 07	4693 + 47	12	4	14.0
4706 + 29	4765 + 67	4	6	9.0
4776 + 13	4868 + 31	11	10	10.5
4881 + 14	4927 + 53	3	4	17.0
4944 + 32	5002 + 28	10	4	30.0
5019 + 06	5069 + 43	2	4	20.0
5086 + 22	5168 + 82	9	9	9.5
5179 + 27	5274 + 37	1	10	12.2
Total	112,662 ft (21.3 mi)	15	92	204.2

^aNuclear Excavation Design (Preliminary)—Route 25, U. S. Army Corps of Engineer Nuclear Cratering Group, IOCS Memorandum NCG-1201-25-31, Ser. NCG-26 (December 1967).

Table A-6. Detonation schedule for interoceanic sea-level canal on Route 25E (April 1969).^a

Stations		Salvo No.	No. of explosives	Total yield (Mt)
From	To			
0 + 00	80 + 00	1	5	3.0
80 + 00	126 + 00	2	5	5.0
126 + 00	195 + 00	3	7	3.5
195 + 00	270 + 00	4	9	5.0
270 + 00	315 + 00	5	5	5.0
315 + 00	366 + 00	6	5	7.5
366 + 00	426 + 00	7	5	12.5
426 + 00	477 + 00	8	5	7.5
477 + 00	535 + 00	9	5	5.0
535 + 00	583 + 00	10	5	5.0
583 + 00	654 + 00	11	8	4.5
654 + 00	728 + 00	12	9	4.5
728 + 00	774 + 00	13	5	5.0
774 + 00	820 + 00	14	5	5.0
820 + 00	865 + 00	15	5	5.0
865 + 00	910 + 00	16	5	5.0
910 + 00	957 + 00	17	5	5.0
957 + 00	1001 + 00	18	5	5.0
1001 + 00	1046 + 00	19	5	5.0
1046 + 00	1095 + 00	20	5	5.0
1095 + 00	1176 + 00	21	10	5.0
1176 + 00	1275 + 00	22	10	5.0
1275 + 00	1365 + 00	23	10	5.0
Total		23	143	123.0

^aJohn Toman, Route 25-E Detonation Plan, LRL Internal Memorandum UOPKC 69-29 (April 7, 1969).

Table A-7. Revised detonation schedule for interoceanic sea-level canal on Route 25E (August 21, 1969).^a

Stations		Detonation identification	No. of explosives	Total yield (Mt)
From	To			
91 + 70	157 + 10	E	10	5.3
165 + 15	273 + 50	F	12	5.2
281 + 55	328 + 35	G	7	5.3
338 + 65	371 + 65	H	5	5.6
384 + 55	429 + 55	I	5	13.0
444 + 55	487 + 55	J	5	9.5
500 + 45	546 + 75	K	7	5.4
556 + 10	632 + 40	L	7	6.4
642 + 70	716 + 45	M	16*	5.8*
725 + 55	757 + 85	N	5	3.9
766 + 05	802 + 00	O	5	5.9
814 + 90	850 + 85	P	5	5.4
861 + 15	898 + 90	Q	5	6.5
912 + 95	955 + 95	R	5	9.0
968 + 85	1011 + 10	S	6	5.4
1020 + 45	1072 + 60	T	8	4.0
1081 + 95	1143 + 15	U	9	5.1
Total	105,145 ft (20.0 mi)		122	106.7

*Detonation M includes seven explosives for T-row interception of the Truando River

River Diversion Channels

0 + 00	94 + 20	A	10	2.8
0 + 00	37 + 50	B	6	0.9
0 + 00	66 + 85	C	7	3.7
7200	right centerline at 674 + 80	D	1	1.5
Total			24	8.9

^aThis detonation program was agreed upon by LRL and the Nuclear Cratering Group (NCG). It will be incorporated in Appendices 12 and 13 of Annex V-Engineering Feasibility Study, Interoceanic Canal Studies and will be used as the basis for that entire study.

APPENDIX B

RESIDENTIAL COMPLAINTS CALCULATIONS

The following calculations are based on the April 1969 shot schedules for Routes 17 A and 25E. Maximum PSAA values are taken from ERC's band-pass filter prediction^{*} and converted to 10% damping. We have carefully considered the effect of repeated detonations. Because of many uncertainties involved in this problem, we simply sum up the percentages of complaints due to each salvo. For rural areas, and some cities where the number of structures are not available, we tentatively assign six persons per structure. This figure may be too conservative. However, as mentioned in the text of this UCIR, the percentages of complaints for rural areas and some cities will be revised when appropriate data are available. Tables B-1 through B-3 are based on the data from John A. Blume and Associates[†]. Table B-1 shows the distance from Routes 17A and 25E to some cities in Colombia and Panama. Table B-2 shows building distribution in some cities in Colombia. Table B-3 shows the cost of different types of structures. Estimations of residential damage (Tables B-4 and B-5) for Routes 17A and 25E are self-explanatory.

^{*} Interoceanic Canal Ground Motion Report (Main report and App. 1-4), Environmental Research Corp., Alexandria, Va. (September 29, 1967). (App. 2, 3, 4 are CFRD-DI)

[†] Structural Effects from Nuclear Excavation on Routes 17 and 25, John A. Blume and Associates, Research Division, preliminary draft (1969).

Table B-1. Distance from Routes 17A and 25E to cities.

COLOMBIA

<u>City</u>	<u>Distance (km) from Routes</u>	
	<u>17</u>	<u>25</u>
Barranquilla	405	525
Bogota	630	465
Bucaramanga	530	480
Cali	625	420
Cartagena	300	435
Manizales	495	315
Medellin	385	230
Monteria	220	260
Pereira	515	320
Quibdo	385	180

PANAMA

Colon	230	360
Panama City	180	300
Santiago	360	395

Table B-2. Building distribution in cities of Colombia.

<u>No. of stories</u>	<u>Barranquilla</u>	<u>Bogota</u>	<u>Cali</u>	<u>Cartagena</u>	<u>Medellin</u>	<u>Manizales</u>
1	66,656	112,547	78,184	29,761	86,814	13,226
2	1,530	58,408	9,524	1,298	16,803	8,949
3	226	6,502	1,078	160	2,517	1,769
4	84	2,231	290	23	469	177
Total	68,496	179,688	89,076	31,242	106,603	24,121

Table B-3. Structure cost in U. S. dollars.

Structure type	Cost per structure, U.S. dollars	
	Colombia	Panama
<u>1- and 2-story:</u>		
Villages	550	1,600
Towns <10,000	980	3,200
Towns 10,000-100,000	1,470	5,000
(Cities >100,000	1,980	8,400
<u>3- and 4-story:</u>		
Towns <10,000	9,230	None
Towns >10,000	14,770	56,400
<u>5- to 8-story:</u>		
Cities <100,000	30,260	132,700
Cities >100,000	34,580	132,700
<u>9 stories or more</u>	Reported cost	Reported cost

Table B-4. Calculations of residential complaints (Route 17A).

Salvo yield (Mt)	Panama 180 km ^c		Monteria 220 km ^c		Cartagena 300 km ^c		Medellin 385 km ^c		Barranquilla 405 km ^c		Manizales 495 km ^c		Cali 625 km ^c	
	180 km ^b		230 km ^b		315 km ^b		385 km ^b		420 km ^b		495 km ^b		625 km ^b	
	PSAA ^a	% of complaints	PSAA ^a	% of complaints	PSAA ^a	% of complaints	PSAA ^a	% of complaints	PSAA ^a	% of complaints	PSAA ^a	% of complaints	PSAA ^a	% of complaints
3.5	11.0	0.15	8.9	0.085	7.36	0.046	6.80	0.037	6.32	0.029	5.55	0.0185	4.78	0.0114
4.0	12.7	0.24	9.9	0.115	8.21	0.064	7.65	0.055	7.03	0.041	6.13	0.0265	5.33	0.0167
4.0	12.7	0.24	9.9	0.115	8.21	0.064	7.65	0.055	7.03	0.041	6.13	0.0265	5.33	0.0167
5.0	15.0	0.35	12.0	0.195	9.90	0.115	9.25	0.095	8.54	0.075	7.40	0.0470	6.46	0.0315
4.5	13.7	0.27	10.95	0.150	9.06	0.088	8.45	0.073	7.83	0.057	6.70	0.0345	5.90	0.0235
5.0	15.0	0.35	12.0	0.195	9.90	0.115	9.25	0.095	8.54	0.075	7.40	0.0470	6.46	0.0315
5.0	15.0	0.35	12.0	0.195	9.90	0.115	9.25	0.095	8.54	0.075	7.40	0.0470	6.46	0.0315
5.0	15.0	0.35	12.0	0.195	9.90	0.115	9.25	0.095	8.54	0.075	7.40	0.0470	6.46	0.0315
5.0	15.0	0.35	12.0	0.195	9.90	0.115	9.25	0.095	8.54	0.075	7.40	0.0470	6.46	0.0315
5.0	15.0	0.35	12.0	0.195	9.90	0.115	9.25	0.095	8.54	0.075	7.40	0.0470	6.46	0.0315
4.0	12.7	0.24	9.9	0.115	8.21	0.064	7.65	0.055	7.03	0.041	6.13	0.0265	5.33	0.0167
5.0	15.0	0.35	12.0	0.195	9.90	0.115	9.25	0.095	8.54	0.075	7.40	0.0470	6.46	0.0315
4.0	12.7	0.24	9.9	0.115	8.21	0.064	7.65	0.055	7.03	0.041	6.13	0.0265	5.33	0.0167
4.0	12.7	0.24	9.9	0.115	8.21	0.064	7.65	0.055	7.03	0.041	6.13	0.0265	5.33	0.0167
4.5	13.7	0.27	10.95	0.150	9.06	0.088	8.45	0.073	7.83	0.057	6.70	0.0345	5.90	0.0235
5.5	16.2	0.42	12.8	0.230	10.80	0.140	9.90	0.115	9.15	0.091	7.92	0.0590	6.98	0.0395
6.0	17.1	0.48	13.63	0.270	11.66	0.180	10.60	0.130	9.70	0.110	8.45	0.0730	7.50	0.0500
5.0	15.0	0.35	12.0	0.195	9.90	0.115	9.25	0.095	8.54	0.075	7.40	0.0470	6.46	0.0315
5.5	16.2	0.42	12.8	0.230	10.80	0.140	9.90	0.115	9.15	0.091	7.92	0.0590	6.98	0.0395
6.0	17.1	0.48	13.63	0.270	11.66	0.180	10.60	0.130	9.70	0.110	8.45	0.0730	7.50	0.0500
13.5	31.8	1.90	24.9	1.150	23.40	1.000	19.90	0.695	18.30	0.580	15.95	0.4100	14.40	0.3200
5.5	16.2	0.42	12.8	0.230	10.80	0.140	9.90	0.115	9.15	0.091	7.92	0.0592	6.98	0.0395
5.0	15.0	0.35	12.0	0.195	9.90	0.115	9.25	0.095	8.54	0.075	7.40	0.0470	6.46	0.0315
5.0	15.0	0.35	12.0	0.195	9.90	0.115	9.25	0.095	8.54	0.075	7.40	0.0470	6.46	0.0315
5.0	15.0	0.35	12.0	0.195	9.90	0.115	9.25	0.095	8.54	0.075	7.40	0.0470	6.46	0.0315
4.5	13.7	0.27	10.95	0.150	9.06	0.088	8.45	0.073	7.83	0.057	6.70	0.0345	5.90	0.0235
Total % complaints:		3.78		5.440		3.560		2.781		2.228		1.4577		1.0189
No. of structures:		70,000	Monteria	8,340		31,242		106,603		68,496	Manizales	24,121	Cali	89,076
			Colon	10,030							Bucaramanga	37,000	Bogota	179,688
No. of complaints:		6,350	Monteria	454		1,113		2,965		1,525	Manizales	352	Cali	908
			Colon	544							Bucaramanga	540	Bogota	1,830

^aPseudoabsolute acceleration spectrum in cm/sec², 10% damping.^bDistance in km for calculating response spectra.^cActual distance in km from Route 17A divide point to the city of interest.

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^aPseudoabsolute acceleration spectrum in cm/sec², 10% damping.
^bDistance in km for calculating response spectra.
^cActual distance in km from Route 25E divide point to the city of interest.

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