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a theoretical evaluation of design ground seismic motions for pipelines in the yukon territory and mackenzie valley

H. S. HASEGAWA

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Abstract. A proposed Mackenzie Valley pipeline route is partitioned into three seismic zones that are related to the calculated acceleration contours for a 100-year-return period of Stevens and Milne. A set of design ground seismic motion parameters is calculated for each zone. The magnitude of these ground motion parameters should be thought of as sustained vibrations that are representative of the seismic activity to be expected on firm ground for the specified return period. Isolated extreme peaks could be a factor of four or even five times greater.

For the section of the proposed corridor where the acceleration contours reach their largest value (west of Fort McPherson in the Richardson Mountains) a set of design ground seismic motion is as follows: 0.25g, 30 cm/sec (12 inches/sec) and 30 cm (12 inches) for ground acceleration, velocity and displacement respectively. For an adjacent region where acceleration contours reach an intermediate level, the corresponding ground motion parameters are 0.11g, 13 cm/sec (5 inches/sec) and 13 cm (5 inches). For the remainder of the proposed corridor where the acceleration contours reach their smallest levels (most of the proposed corridor lies in this region) ground motion parameters are 0.09g, 10 cm/sec (4 inches/sec) and 5 cm (2 inches). Estimated maximum strains are of the order of 10^{-6} for the permanent offset and 10^{-5} to 10^{-4} for transient or dynamic strain. For imperfect coupling between ground and pipeline the corresponding strains induced in the pipeline structure will be proportionately less, depending on the degree of coupling between ground and structure.

Résumé. Le tracé proposé du pipeline dans la vallée du Mackenzie est divisé en trois zones séismiques, reliées aux courbes d'accélération calculées pour une période de retour de 100 ans de Stevens et Milne. Un ensemble de paramètres de séismicité est calculé pour chaque zone. L'ampleur de ces paramètres doit être conçue sous forme de vibrations soutenues, représentatives de l'activité séismique à prévoir sur un terrain solide pour la période spécifiée de retour. Les points isolés extrêmes pourraient constituer un facteur de magnitude quatre ou même de grandeur cinq.

Quant à la section du corridor proposé où les courbes d'accélération atteignent leur plus forte intensité (à l'ouest de Fort McPherson dans les monts Richardson), la séismicité du tracé projeté se présente ainsi: 0.25 v, 30 cm/sec (12 pouces/sec) et 30 cm (12 pouces) pour l'accélération tellurique, la vitesse et le déplacement, respectivement. Dans une région adjacente, où les courbes d'accélération atteignent une intensité moyenne, les paramètres de mouvements telluriques correspondants sont 0.11 v, 13 cm/sec (5 pouces/sec) et 13 cm (5 pouces). Pour le reste du corridor proposé, où les courbes d'accélération atteignent leur intensité minimale (la majorité du corridor proposé s'étend dans cette région), les paramètres de mouvements telluriques sont 0.09 v, 10 cm/sec (4 pouces/sec) et 5 cm (2 pouces). Les tensions mécaniques maximales sont de l'ordre de 10^{-6} pour la compensation permanente et de 10^{-5} à 10^{-4} pour la tension passagère ou dynamique. Dans un contact imparfait entre le sol et le pipeline, les tensions transmises dans la structure du pipeline seront proportionnellement moindres, suivant le degré de contact entre le sol et la structure.

Introduction

Variability in seismic risk in the Yukon and adjacent areas of the Northwest Territories is illustrated in a recent report by Stevens and Milne (1973). Utilizing available seismic information on earthquakes (1899-1970) that have either originated in this region or have originated elsewhere but have generated intensities in this region high enough to have been felt, these authors have constructed two different types of maps depicting seismic risk in this region. It is the information presented in those maps based on a statistical approach to seismic zoning (see Milne and Davenport, 1969) that will be used in the present report.

Figures 1 and 2 show the proposed pipeline routes that are being considered north of 60° latitude together with available information on the seismicity (1899-1970) of this region superimposed upon a physiographic (Douglas, 1970) and a tectonic (Douglas, 1970) map respectively. Figure 3 illustrates an evaluation of the seismic risk in the region of interest in the form of acceleration contours for a 100-year-return period (from Stevens and Milne, 1973). From a glance at Figures 1, 2 and 3, it can be seen that the region of maximum seismic risk in the proposed pipeline route through the Yukon Territory and along the Mackenzie River lies in the sector that traverses the Richardson Mountains. In this region the proposed route intersects a seismically active zone in which the pipeline and associated structures could be subjected to strong seismic vibrations.

This report is concerned primarily with a determination of ground motion parameters that are indicative of the level of seismic activity expected in the proposed pipeline corridor over an appropriate time interval, namely a return period of 100 years. This set of strong ground motion parameters–acceleration, velocity and displacement–are designated as the "design earthquake" ground motion parameters. These values can be used by the design engineer as input into soil and structural design so as to enable the pipeline and associated structures to successfully resist the strong seismic vibrations expected from the "design earthquake".

Favourable conditions for estimating the degree of seismic activity obtain when both the earthquake history and the tectonics of a seismically active region are known in detail (e.g. some areas of California adjacent to San Andreas fault). From this information seismologists can evaluate ground motion parameters for an appropriate design earthquake. This information is useful to the design engineer

Figure 1. Seismicity (1899-1970) and proposed pipeline route (thick dashed line) superimposed upon physiographic map of Yukon and bordering portion of Northwest Territories (physiographic map from Douglas).

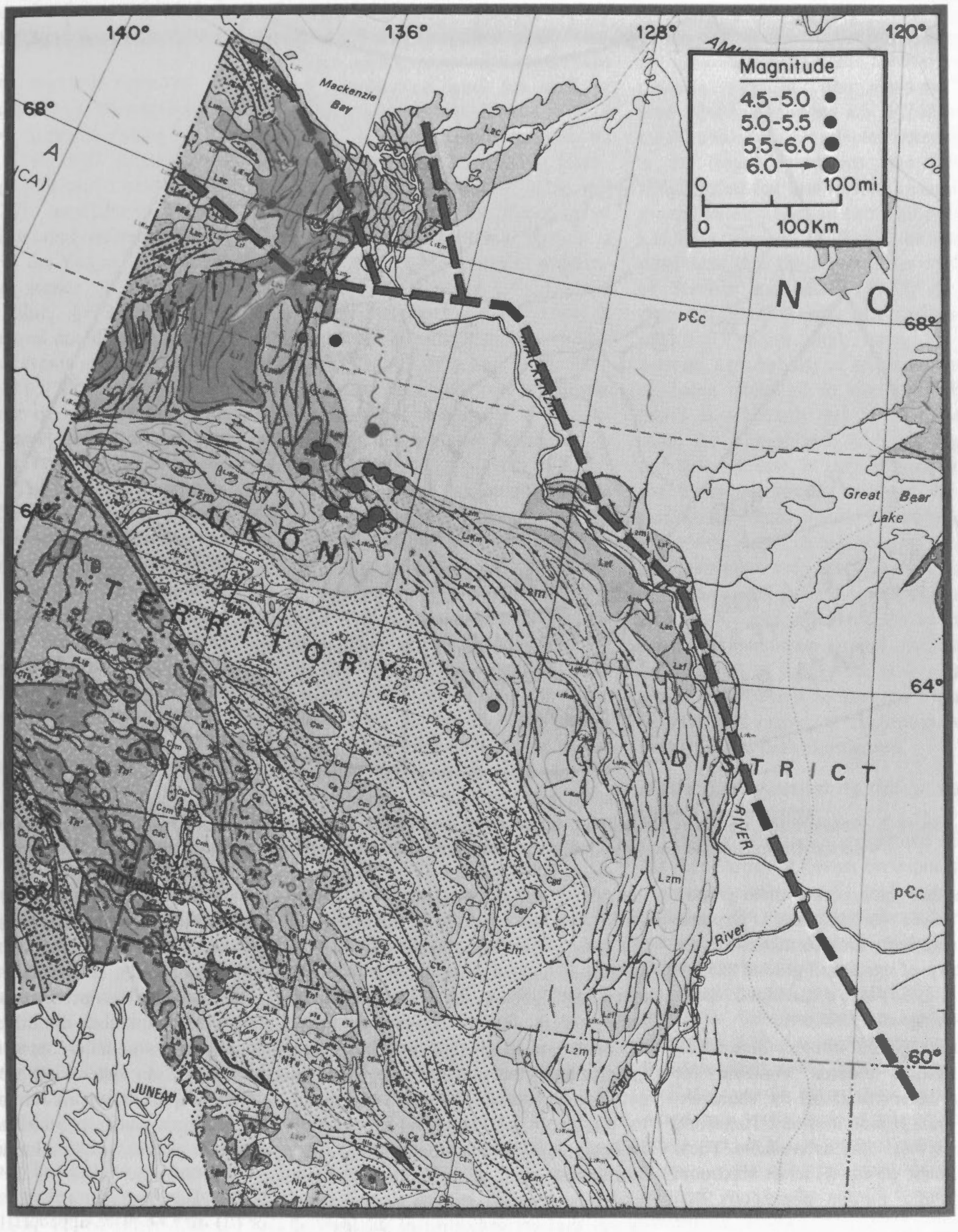

Figure 2. Seismicity (1899-1970) and proposed pipeline route (thick dashed line) superimposed upon tectonic map of Yukon and bordering portion of Northwest Territories (tectonic map from Douglas).

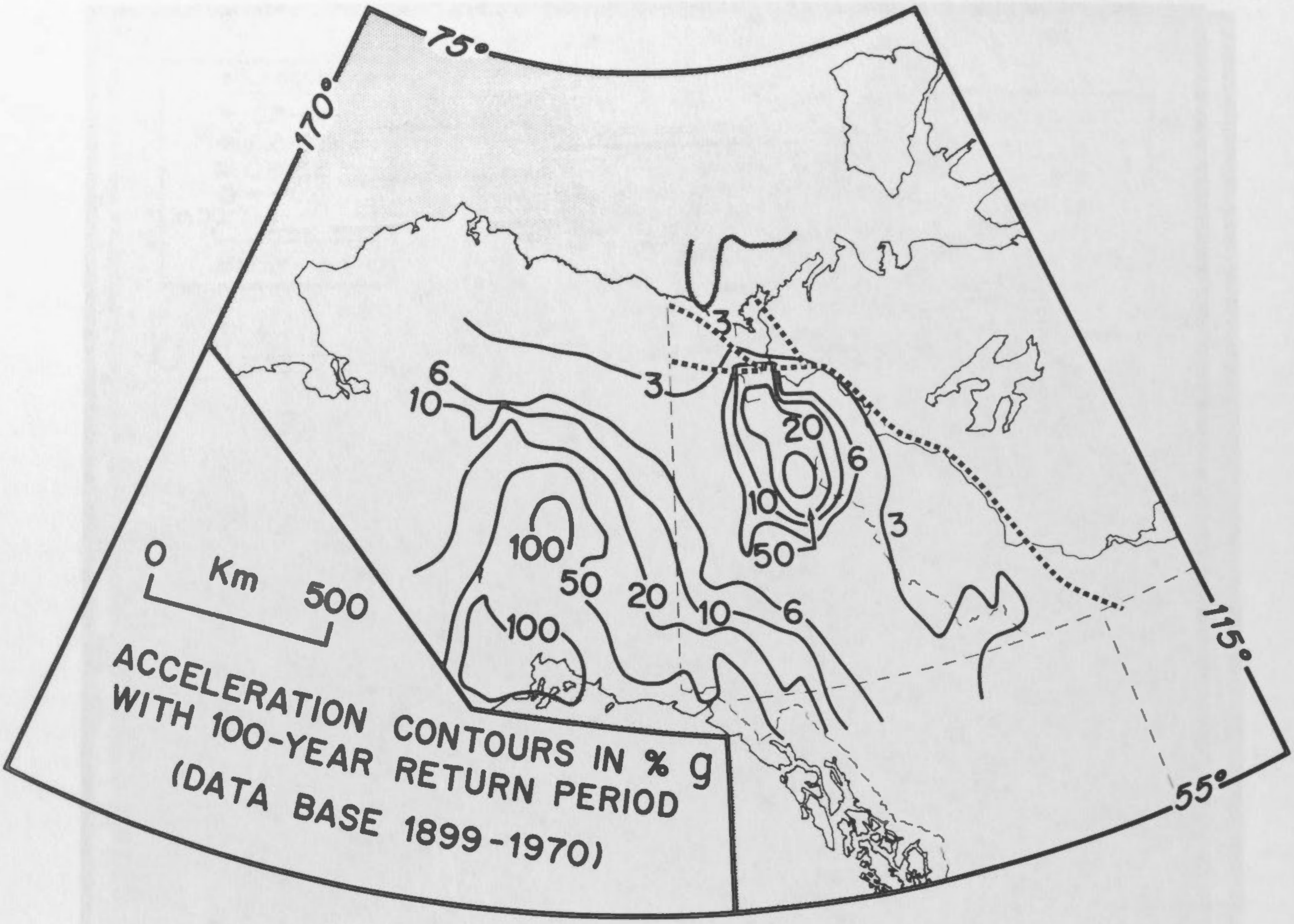

Figure 3. Acceleration contours for Yukon, bordering Northwest Territories and Alaska for a 100-year-return period (from Stevens and Milne). Proposed pipeline route represented by thick dashed line.

who can then incorporate these ground motion values (or associated response spectra) together with information on the time history of significant ground motion (see Perez, 1973) into a combined static-dynamic design of a structure.

For the region of interest there are no strong motion records available for obtaining observations on the characteristics of local ground motions. Therefore, there are several options available. These are as follows: we can (i) select maximum strong ground motion parameters that have been recorded anywhere in the world for any earthquake equivalent, or slightly greater, in magnitude to the largest magnitude earthquake that has occurred within or close to the region of interest (ii) estimate a physically plausible minimum focal depth that can be expected for the largest magnitude earthquake that has occurred in the region of interest; next assume that the structure of interest is located on the earth's surface immediately above the focus, that is at the epicentre; finally carry out the same procedure as in (i) but subject to the hypocentral (from earthquake focus to detector on surface) distance being equal to the depth of focus (iii) incorporate available information on seismicity and seismic risk with an appropriate seismic model to generate ground motion parameters that are indicative of the level of seismic activity expected over a suitable time span. The ground motion values calculated by this method are average amplitudes with a reasonable duration rather than extreme isolated peak values. These peaks, which have been noticed on some recent accelerograms, can be caused by unusual soil interaction, by focusing of seismic waves and other circumstances and consequently, are unpredictable.

Ground motion parameters evaluated by the three methods outlined above can be expected to differ appreciably. The selection of an appropriate set of values depends upon the anticipated response of the structure under consideration. If the structure under consideration is expected to respond to an isolated peak ground acceleration, then the values shown in (i) or (ii) may be more appropriate. The use of (ii) presumes knowledge of focal depth. However, if the structures under consideration can be adequately represented by single-degree-of-freedom oscillators with damping of about 5 per cent critical, then the values representative of

(iii) are more appropriate (see, for example, Perex, 1973).

Seismicity and tectonic features

Figures 1 and 2 show the seismicity in the Central and Northern Yukon for the time interval 1899-1970 superimposed upon a physiographic and a tectonic map (Douglas, 1970) respectively of this region. (For a detailed reference list on the seismicity of the Yukon and adjacent territories, the reader is referred to Stevens and Milne, 1973.) Since the published epicentral coordinates of many of the historical events could, in general, be in error by ±1°, we cannot associate with any degree of firmness the larger events in the past with local tectonic features such as faults observed at the earth's surface. The correlation of earthquake distribution with surface faulting has not yet been well established in this region, although recent field studies of smaller earthquakes with a temporary network of seismic stations are making some progress in this direction in the Wernecke Mountain and Richardson Mountains regions farther south (Leblanc, private communication, 1973).

Outline of computational procedure

The proposed pipeline corridor will be partitioned into three seismic zones. With reference to Figure 3 (from Stevens and Milne, 1973) these zones are as follows: the region in which the acceleration contours for a 100-year-return period lie between 0.06g and approximately 0.10g will be referred to as the zone of maximum seismic ground motion; the adjacent region in which the acceleration contours (for the same return period) lie between 0.03g and 0.06g will be referred to as the zone of intermediate seismic ground motion; the remainder of the proposed corridor for which the acceleration contours are of the order of 0.03g will be referred to as the zone of minimum seismic ground motion.

Because it is of paramount importance to safeguard the pipeline and associated facilities against failure and because of an uncertainty factor of about two in the acceleration contours, a safety factor of 2.5 will be applied when determining an appropriate design earthquake ground acceleration level for each of these three zones. Thus, for the zone of maximum seismic ground motion an acceleration level of 2.5 x 0.10g (maximum acceleration contour) = 0.25g will be ascribed. Similarly for the zone of intermediate seismic ground motion a value of 2.5 x 0.045g (mean of acceleration contour in this region) = 0.11g will be ascribed. Finally, for the zone of minimum seismic ground motion, a level of 2.5 x 0.03g = 0.075g may be ascribed. However, in view of recent seismic activity south of this zone (to be described later) this tentative value may be increased to 0.09g.

Since the above acceleration values are related to ground motion, they are appropriate as input parameters for the design of soil structures and completely buried structures (e.g. a buried pipeline). However, for structures that either rest on the ground surface or extend above the surface, a comparatively lower level of ground motion can be used for design purposes. This is due to the energy absorbed (dissipated) while in the inelastic (ductile) region, thereby reducing the elastic response of the structure by a factor equal to the ductility factor.

Ground motion parameters calculated in this report are based on a 100-year-return period. The use of equation (2), p. 5 of Stevens and Milne (1973) enables one to calculate the ratio of accelerations for any two return periods of interest. Consequently, acceleration levels for a desired return period can be evaluated using equation (2) in conjunction with an acceleration calculated for a particular return period.

The "safety margin" that a design engineer incorporates into a pipeline system will depend upon, among other factors, return period, percentage of critical damping and ductility factor. In structural terms, these are related to strength, stiffness and elasto-plastic behaviour, respectively.

Data input to a theoretical design earthquake

Input parameters to a theoretical design earthquake for the region of maximum seismic risk, i.e. the section of the pipeline corridor that traverses the Richardson Mountains are as follows: a magnitude of $6^1/_2$ is selected because this is the largest magnitude (see Meidler, 1962) listed for this region; a maximum ground acceleration on firm soil of 0.25g has been selected. It should be emphasized here that the acceleration contours of Stevens and Milne (1973) do not represent deterministic peak values but statistical values that have, on the average, a probability of one-in-a-hundred of being exceeded in one year. Focal depth is arbitrarily set to a minimum value for a magnitude $6^1/_2$ earthquake and this estimate, in turn, depends upon the linear dimensions assumed for the earthquake fault plane; epicentral distance is no longer an independent variable but has a value such that, for a magnitude $6^1/_2$ earthquake the theoretically generated earthquake accelerogram spectrum predicts a maximum ground acceleration on firm soil of 0.25g; the fault plane is arbitrarily oriented so that the radiation pattern will have a maximum value (unity) in the desired direction.

Method of calculating design earthquake parameters

Having selected a magnitude ($6^1/_2$) for this particular design earthquake and a ground acceleration (0.25g), we wish to calculate the remaining parameters of interest, namely ground velocity and ground displacement.

This is carried out in an indirect way and is as follows: first an appropriate multiplier is used to evaluate an acceleration level that a 0%ζ (critically damped) oscillator would experience when subjected to a predetermined ground acceleration (e.g. 0.25g in present case). Then from a suite of appropriate theoretical response curves that are a function of magnitude ($6^1/_2$ in the present case) and hypocentral distance (which is to be determined), the particular curve that has the predetermined acceleration response level is selected. A hypocentral distance that is associated with the selected curve gives us the important "distance" parameter insofar as body waves from a design earthquake are concerned. For surface waves, however, the important "distance" parameters are focal depth and epicentral distance. The theoretical response curves that we are referring to are the unnormalized Fourier amplitude spectrum (FS) curves of ground acceleration and are related to velocity response spectrum (SV) by (Trifunac, 1972)

$$|FS|_{max} \leq SV_{0\%\zeta}$$

where ζ represents critical damping of a single-degree-of-freedom oscillator.

Design engineers find it convenient to work with velocity response (SV) curves or the approximate pseudo-velocity response (PSV) curves. Although there is no obvious technique to generate theoretically either of these response curves, it is possible, however, to generate theoretically Fourier amplitude spectrum (FS) curves that are reasonably close facsimiles to velocity response ($SV_{0\%\zeta}$) curves (see, for example, Hasegawa, 1974).

For structural design purposes, it is convenient (and generally sufficiently accurate) to partition FS curves (see, for example, Figure 4) into three frequency (or period) bands. In each of these ranges the tangential line segments shown are used to evaluate the appropriate response parameters for a $0\%\zeta$ single-degree-of-freedom oscillator. Velocity response ($SV_{0\%\zeta}$) is read directly from the figure, acceleration response ($SA_{0\%\zeta}$) by multiplying by an appropriate angular frequency in the frequency range of interest and displacement response ($SD_{0\%\zeta}$), by dividing by an appropriate angular frequency in the selected frequency range.

From the three response value namely $SA_{0\%\zeta}$, $SV_{0\%\zeta}$ and $SD_{0\%\zeta}$, we can evaluate the desired ground motion parameters by dividing by appropriat damping scale factors (see, for exampl Newmark and Hall, 1969; Hasegaw 1974). The resulting ground acceleratio value should, of course, equal the preselected value. Ground motion parameters (acceleration, velocity and displacement) thus evaluated should be thought of as being representative not of an isolated large amplitude peak but of smaller amplitudes of longer duratio The reason for this qualifying statemen is that the selected FS curve (see Figur

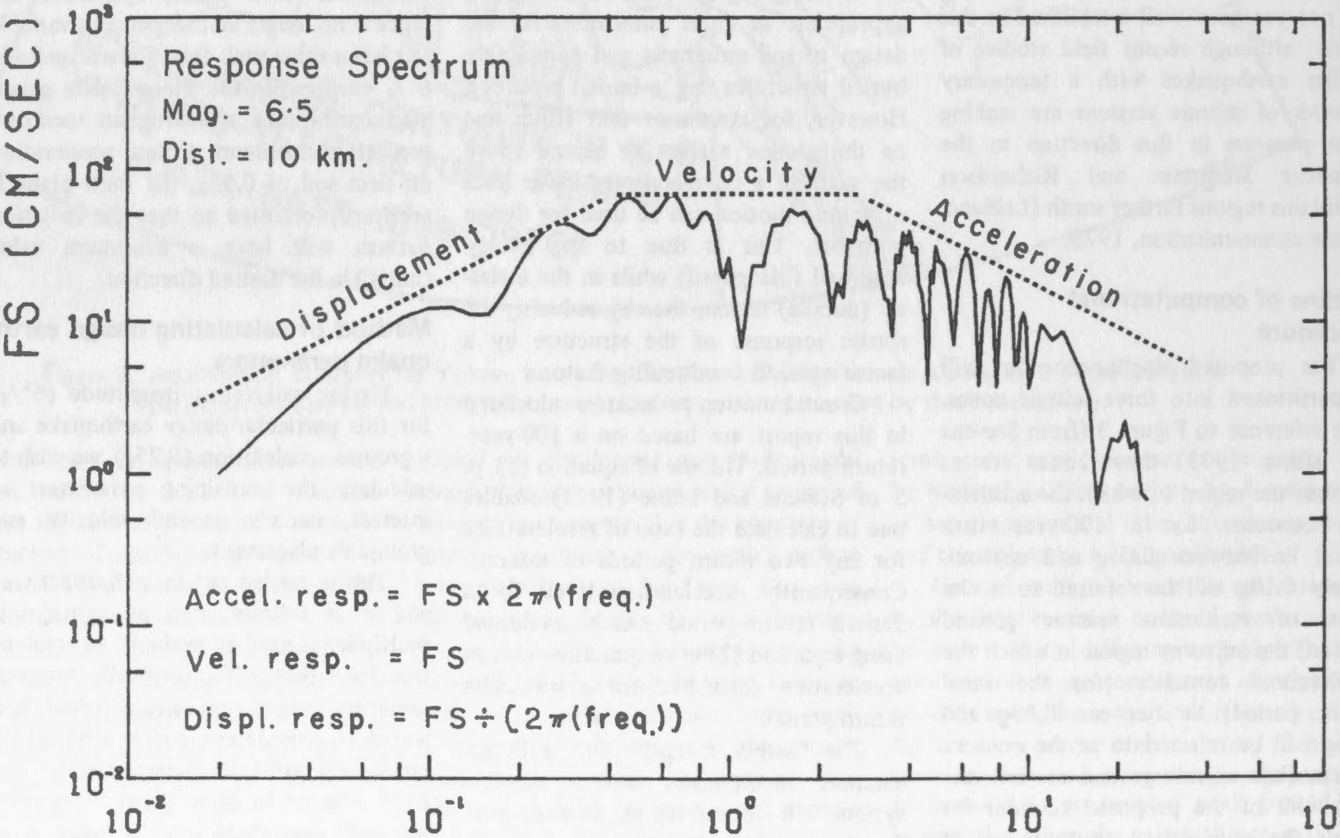

Figure 4. Acceleration, velocity and displacement response values for a $0\%\zeta$ oscillator are represented approximately by the straight line segments tangent to the Fourier amplitude spectrum (FS) curves of ground acceleration (due to the direct shear wave). The above FS curve is representative of the zone of maximum seismic risk in the proposed pipeline corridor.

4) does not contain isolated large amplitude peaks but a number of smaller amplitude peaks. In subsequent evaluations of response spectra for appropriate damping factors, one must work from the ground motion parameters and not from the prototype FS curve, nor more explicitly from the simulated response values for a 0%ζ single-degree-of-freedom oscillator.

A theoretical design earthquake spectrum

Table I lists the parameters selected for a theoretical design earthquake for the zone of maximum seismic risk. The data base used to generate the design earthquake spectra that are used in this report are the Fourier amplitude spectrum (the FS curves) of California earthquake accelerograms (from Hudson, 1972). This choice is necessitated because of an insufficient number of western Canada accelerograms.

The response spectrum parameters associated with the direct shear waves radiated from this design earthquake are readily evaluated from Figure 4 by the method outlined previously and are shown in Table II. The amplification factor/term includes crustal wave attenuation, crustal reverberations and surface (Love) wave contributions. Attenuation is significant in the high-frequency end of the spectrum, that is the acceleration flat portion (see Figure 4). Crustal reverberations are generally manifest in the central frequency band; that is in the velocity flat portion. Surface waves often predominate in the low-frequency portion, especially for shallow focus events (assumed 7 km focal depth). In order to avoid underestimating ground motion parameters for the selected design earthquake, we have selected minimum allowable values for the divisor that converts a Fourier amplitude spectrum, or its equivalent, which is the simulated velocity response spectrum (0%ζ), to ground motion; by "minimum allowable", we are referring to mean values reduced by one standard deviation.

Ground motion values shown in Table II are only appropriate over the respective frequency ranges shown in Figure 4. Although an acceleration value of 0.25g is, strictly speaking, only appropriate for frequencies greater than, say, several cps, it is, nevertheless, standard practice for design engineers to utilize this high-frequency acceleration level to evaluate, by means of a suitable multiplier or seismic coefficient, an approximate acceleration level appropriate for the natural period of vibration (T) of a structure. This extrapolated value is then used as input to the calculation of base shear. This acceleration value of 0.25g should be taken into consideration in the dynamic design of any soil or buried pipeline structure for which the natural resonant frequency is greater than several cps. Also this velocity of 30 cm/sec (12 inches/sec), which is appropriate for soils or buried structures for which the natural resonant frequency is close to 1 cps, is an important input into the dynamic design of these components. Finally this displacement of 30 cm (12 inches) may be required to calculate the dynamic response of buried structures with a natural period of the order of several seconds; a resonance phenomenon could develop, resulting in very large deformations.

For comparison purposes, Table III lists the ground motion parameters associated with a magnitude $6^1/_2$ earthquake that are obtained by other authors utilizing either experimental data or an empirical formula. Values for ground acceleration, velocity and displacement that are estimated in this report for magnitude $6^1/_2$ earthquake lie in between those of Newmark and Hall (1973) for magnitudes $6^1/_2$ and 7. Moreover, ground motion values evaluated in this report are (as anticipated) smaller (see Table III) than maximum experimentally observed isolated peak values.

The selection of an appropriate set of ground motion parameters depends upon the anticipated structural response. If a structure can be represented adequately by a single-degree-of-freedom oscillator with damping of 2–7%ζ, then the response spectrum (Velocity Response Envelope Spectrum) graphs of Perez (1973) indicate that velocity response is greater for smaller levels of ground acceleration of many cycles than for an isolated extreme peak in acceleration. Since

Table I. Theoretical Design Earthquake Parameters

Magnitude	Fault length (km)	Fault width (km)	Dislocation (cm)	Focal depth (km)	Epicentral distance (km)	Hypocentral distance (km)
6.5	18	11	75	7	7	10

Table II. Design Earthquake Spectrum Parameters

	Acceleration (gravities)	Velocity (cm/sec)	Displacement (cm)
FS* (direct shear wave)	1.15	70	25
Amplification factor/term	x 1	x 1.5 (crustal reverberation) contribution	† (200 per cent) (surface wave) contribution
FS (total shear plus surface wave)	1.15	105	75
Divisor † (to obtain ground motion)	4.6	3.5	2.5
Ground motion parameters	0.25	30	30

*FS = Fourier amplitude spectrum (from Figure 4) simulates a velocity response (SV) curve with 0%ζ (critical damping).

†Minimum value assumed for scalar divisor: these values were obtained from the average values and standard deviations in Hasegawa, 1974.

ground motion parameters evaluated in this report and by Newmark and Hall (1973) are representative of smaller average amplitude levels of ground vibration of many cycles and not for an isolated peak, then for pipelines and appurtenant structures that satisfy the criteria stated in the previous statement, the response graphs of Perez would indicate the appropriateness of utilizing, not isolated peak values, but the comparatively smaller values listed in Table III.

Uncertainties in estimates of design earthquake ground motion values utilizing the method outlined above are difficult to assess for several reasons: the mechanism by which the high-frequency (acceleration flat) components is generated is not fully understood; both the centre frequency (velocity flat) components and the low-frequency (displacement flat) components depend strongly on the linear dimensions of the fault, which for a specified magnitude can vary considerably. However, the tendency throughout theoretical calculations was to select values that tended not to underestimate ground motion, but which stayed within specified error limits. Schnabel and Seed (1973) have determined empirically the margin of scatter in maximum acceleration measurements in rock; specifically at 10 km from a magnitude $6^1/_2$ earthquake their range is about 0.24g. If we assume that this experimentally determined range of uncertainty is applicable to the ground acceleration value of 0.25g shown in Table III (and this would appear to be a reasonable assumption) then the uncertainty in ground motion acceleration would be ±50 per cent. Uncertainties in estimates of ground velocity are about ±30 per cent (see, for example, Page *et al.*, 1972). Uncertainties in ground displacement depend, in a large part, upon the amount of surface wave generated as compared with long-period body (shear) waves. In the present case we have assumed at long periods (> 2 seconds) that the contribution from surface waves is twice that from body waves; an uncertainty factor of ±30 per cent is assigned.

Utilizing a method of calculating design earthquake ground motion parameters described previously and the uncertainty factors discussed above, we have evaluated the following ground motion parameters for each of the three seismic zones of the proposed pipeline corridor. For the section of the proposed corridor where the acceleration contours for a 100-year-return period are largest, a set of seismic ground motion parameters is as follows: acceleration 0.25g ±0.12g; velocity 30 cm/sec ±10 cm/sec; displacement 30 cm ±9 cm. For the zone in which the acceleration contours reach an intermediate level, a set of ground motion values is based on the selection of a ground acceleration value that is 2.5 times an average (of 0.045g) for this region: acceleration 0.11g ±0.05g; velocity 13 cm/sec ±4 cm/sec; displacement 13 cm ±4 cm. For the remainder of the proposed corridor a ground acceleration value that is 2.5 times a representative value of 0.03g would be 0.075g. However, in recent years several seismic events have occurred south of this region and if we take these events into consideration in evaluating a set of ground motion values for this region we get the following: acceleration 0.09 ±0.05g; velocity 10 cm/sec ±3 cm/sec; displacement 5 cm ±2 cm.

The earthquakes mentioned in the previous paragraph are the Snipe Lake, Alberta, earthquake of March 8, 1970 and the Bengough, Saskatchewan earthquake of July 26, 1972. The U.S. Coast and Geodetic Survey PDE cards list the Snipe Lake event as having a magnitude

Table III. Ground Motion Parameters for a Magnitude $6^1/_2$ Earthquake

Reference	Hypothetical focal depth (km)	Assumed epicentral distance (km)	Hypocentral distance (km)	Acceleration (gravities)	Velocity (cm/sec)	Displacement (cm)	Comments
Page *et al.* (1972)			few (3-5)	0.90	100	40	Maximum horizontal acceleration–single components; see Page *et al.* † for qualifying remarks.
Schnabel and Seed (1972)	30 20 10	0 0 0	30 20 10	0.17 ±0.08 0.26 ±0.10 0.42 ±0.12			Average values of maximum acceleration in rock. Hypothetical focal depths are those of present author and not Schnabel and Seed*.
Newmark and Hall (1973)				0.22	28	22	"Effective" and not maximum spike values of design seismic motion. (See Newmark and Hall** for more details.)
Hasegawa (this report)	7	7	10	0.25 ±0.12	30 ±10	30 ±9	Not extreme peak values but those representative of level of seismic activity expected in region under study.

†Page *et al.* (1972) list, in the same table peak accelerations and velocities that are exceeded up to 10 times. That is, they tabulate a "time history" of strong ground motion.

*Schnabel and Seed (1973) display lower and upper bounds expected for average values of maximum acceleration in rock.

**Newmark and Hall (1973) tabulate two sets of values, depending on intensity of earthquake; above values are for more extreme conditions.

(m_b) of 5.1, a focal depth of 9 km and an epicentre of 55.0°N and 116.6°W. The U.S. National Earthquake Information Center PDE cards list the Bengough event as having a 4.3 m_b, a normal focal depth and an epicentre of 49.5°N and 104.8°W. (For further information regarding the Snipe Lake event the reader is referred to Milne (1970) and for the Bengough event, to Horner *et al.* (1973).) A design earthquake of magnitude $5^1/_2$ and a focal depth of 10 km is assumed for the zone of minimum risk. In order to determine whether surface waves at a distance of approximately 100 km from a magnitude $6^1/_2$ earthquake are of the order of 5 ±2 cm, we have examined a number of strong motion records found in Hudson and Brady (1971): surface wave amplitudes are of the order of 3 to 5 cm, in agreement with our results.

Table IV summarizes design earthquake ground motion levels associated with each of the three seismic zones. These values are appropriate as input into the design of soils and buried structures. For structures that extend above the ground surface, a suitable divisor (ductility factor) should be applied to the values shown in Table IV and the desired response spectrum can be calculated by selecting an appropriate damping factor and applying its related multipliers (see Newmark and Hall, 1973).

Another important factor that should be taken into consideration in the design of the pipeline is the anticipated maximum strain in the pipeline itself. According to Newmark (Alyeska Appendix A-3, 1051) dynamic strains of the order of 6×10^{-4} can cause longitudinal stresses of about 18,000 p.s.i., which according to this author is considered to be high, i.e. capable of damage; consequently if this level of stress is anticipated, then this should be taken into account in the design of the pipeline. Table V shows that strain steps of the order of 2×10^{-6} can be expected at a hypocentral distance of 10 km from a magnitude $6^1/_2$ earthquake (Wideman and Major, 1967). If we assume that the pipeline, being very flexible, can withstand strains of up to 4×10^{-3} ("operating deformation limit" of Newmark), then it would appear that the estimated strain step is not significant. However, the two estimates (one for constant velocity frequency range and the other, for constant displacement) of peak transient or dynamic strain shown in Table V are not insignificant if we take Newmark's criterion regarding the stress/strain level that a pipeline can safely withstand. The above example presumes perfect coupling between pipeline and firm ground; since strain is not continuous between two elastic bodies in welded contact (stress and displacement are) and since there is likely to be imperfect coupling between firm ground and the pipeline, an accurate estimate of strain induced in the pipeline is a difficult task.

The next step, which is the specification of peak response spectrum parameters appropriate for pipelines and associated structures, is the responsibility of the design engineer. If, in the opinion of the design engineer, the structure under consideration can be represented adequately by a single-degree-of-freedom oscillator, with a low damping factor (ζ) then the solution becomes tractable. For this approximate representation of a structure, design engineers can readily calculate a response spectrum envelope from ground motion parameters such as those shown in Table IV by taking into consideration an appropriate reduction (ductility) factor and empirically determined amplification (damping) factors; several examples are presented by Newmark and Hall (1973). The above method, although expedient does not take into account explicitly, but only implicitly, the duration of strong ground vibrations.

Duration of strong ground motion

The method utilized in this report to

Table IV. Design Earthquake and Design Ground Seismic Motions*

Seismic zone	Design earthquake mag.	Distance (hypocentral) km	Acceleration (gravities) ground motion	Velocity (cm/sec) ground motion	Displacement (cm) ground motion
Maximum	$6^1/_2$	10	0.25	30	30
Intermediate	$6^1/_2$	20	0.11	13	13
Minimum	$5^1/_2$	10	0.09	10	5

*For firm ground and for a 100-year-return period.

Table V. Maximum Predicted Strain in Corridor*

	Modulus	Peak strain	Comments
Permanent offset (dislocation at source)	75 cm	2×10^{-6}**	from Figure 6 of Wideman and Major (1967).
Maximum ground displacement (D_m) 10 km from earthquake focus	20 cm	$\simeq 10^{-4}$**	from $\frac{1}{2} \frac{2\pi D_m}{T \cdot \beta}$ (eq. 27 of Major *et al.*, 1964)
Maximum ground velocity (V_m) 10 km from earthquake focus	30 cm/sec	$\simeq 10^{-5}$**	from $\frac{1}{2} \frac{V_m}{\beta}$ (eq. 27 of Major *et al.*, 1964)

Legend:
T = Predominant period in ground motion.
β = Shear wave velocity.
*10 km hypocentral distance from magnitude $6^1/_2$ earthquake.
**Assuming (i) Perfect coupling between ground and pipeline.
(ii) Elastic moduli of pipeline similar to that of ground.

generate strong ground motion parameters is quasi-static in that it does not provide explicit information on the duration of strong ground vibration. Page *et al.* (1972) show that the duration of strong ground motion increases with increasing magnitude; the 0.05g level duration at 10 km from a magnitude $6^1/_2$ earthquake is listed as being 17 sec. This time interval is related to the rupture process and to the volume of the fault region; in some regions crustal reverberations could be a contributing factor.

For sites where there is an appreciable amount of very low-velocity unconsolidated surficial sediments, Trifunac (1971) has shown that a significant part of strong earthquake ground motion can consist of surface waves. The importance of the duration of an approximately sinusoidal wave-train on the response spectrum of a single-degree-of-freedom oscillator with 2–5%ζ is illustrated clearly by Perez (1973). When the natural period of vibration of a structure coincides with the dominant period in a dispersed surface wave train then the response of a structure can be appreciable. This situation could conceivably happen for a structural system in a region where the low-velocity surficial sediments are such that a shallow earthquake could generate a significant amount of short period (0.5 sec–2 sec) surface waves of appreciable amplitude and duration. Then provided the natural period of vibration of the system lies in this period range, a resonance phenomenon could develop, resulting in large-amplitude forced oscillations. However, both conditions are necessary for a resonance phenomenon to exist: dispersed short-period surface waves and a natural period of vibration that coincides with the dominant period in the surface wave train.

Local conditions

Seismically induced ground disturbances such as slope failure, seismic liquefaction (see Lachenbruch, 1970) and the scattering of seismic waves by pronounced topographic relief (see Davis and West, 1973; Viecelli, 1973) are beyond the scope of this report.

A very brief qualitative description will be given of some important effects of seismic waves reacting with local surface and near-surface crustal conditions.

(1) Surficial sediments: Unconsolidated surficial sediments tend in general to (i) diminish ground acceleration amplitude at high frequencies because of attenuation, (ii) enhance ground velocity amplitude in the intermediate frequency range (near 1 cps) due in part to constructive interference, (iii) enhance ground displacement amplitude at low frequencies. When a resonance phenomenon exists, then (ii) and/or (iii) can be appreciable. The amplitude of short-period surface waves is enhanced by surficial sediments.

(2) Permanent fault offset: Calculated dislocations, such as that shown in Table I, can be quite different from fault offsets measured at the surface for very shallow focus events for which the rupture propagates to the surface (see Haskell, 1969). A decoupling of a thin surface layer near the surface is given by Aki (1968) as a possible explanation of this observed difference (smaller relative offset at surface). However, large amplifications (greater relative offset at surface) are also conceivable (Boore *et al.*, 1971). Newmark describes methods of decoupling pipeline from support (ground/pier) so as to overcome this problem.

(3) Permafrost: The mean annual ground temperature for the northern Yukon lies between −10°C and 0°C; theoretical estimates of permafrost thickness range as high as 1,000 metres but in most locations it is doubtful if the thickness exceeds 500 metres (Judge, 1973). For example, (i) measured permafrost thickness in the Eagle Plains at 66°11′N, 138°42′W is 88 m. (ii) in the vicinity of Fort McPherson the thickness ranges from 90–150 m. (iii) along the Arctic coast permafrost thickness increases and the ice content is greater (Judge, personal communication).

If the ice content in the permafrost is appreciable, then the velocity and elastic properties of the permafrost should approach that of ice: e.g. velocity of compressional wave 3.5 km/sec, velocity of shear wave 1.6–2.0 km/sec (Press, 1966); shear modulus 0.033 mb and Poisson's ratio 0.36 (Birch, 1966). Theoretical calculations on the effect on seismic amplitudes of superposing a 400-metre-thick layer of permafrost with the seismic velocities quoted above over a granitic crust indicate an enhancement in both surface and body wave displacement amplitudes. For example, Love (surface) wave displacement amplitudes of periods of the order of several seconds are enhanced by 25 per cent; the displacement amplitudes of SH (body) waves of shorter periods impinging from below at shallow angles upon the permafrost layer, are enhanced by 150 per cent. However, the transmission characteristics of permafrost with respect to ground acceleration for frequencies greater than, say 3 cps, is not known. We fully realize that the above example is an extreme case even for the section of the pipeline corridor near the coastline. It is simply used to give an indication of the response of body and surface waves to a permafrost layer at the surface.

Summary

(1) A set of ground motion parameters has been evaluated for each of three seismic zones in the proposed pipeline corridor. These values should be thought of as being maximum sustained levels that are representative of the seismic activity to be expected on firm ground for a 100-year-return period. The following are ground motion parameters that are input into the design of soils and completely buried structures: for the zone in the proposed corridor where the acceleration contours for a 100-year-return period reach a maximum, acceleration is 0.25g, velocity is 30 cm/sec and displacement is 30 cm; for the zone of intermediate ground acceleration levels, corresponding values are 0.11g, 13 cm/sec and 13 cm; for the zone of minimum ground acceleration levels, values are 0.09g, 10 cm/sec and 5 cm respectively. For above-ground structures that can be represented by a single-degree-of-freedom oscillator with low critical damping factor, the above values should be divided by the ductility factor of the structure. This reduced set of "ground motion parameters" are appropriate for structures that can dis-

ipate some of the input energy while in the inelastic (ductile) region, thereby reducing the elastic vibration levels.

(2) Isolated peak values can be much larger and could well lie outside the estimated margin of error (see Table III). Uncertainties in experimental peak ground motion parameters are assumed to be applicable to these design earthquake ground motion parameters and are based on graphs from Schnabel and Seed (1973) and experimental plots of Page *et al.* (1972); these uncertainty values are ±50 per cent for acceleration, ±30 per cent for velocity and ±30 per cent for displacement, respectively.

(3) Estimates of maximum strains expected in the pipeline corridor are of the order of 10^{-6} for the permanent offset and $10^{-5}-10^{-4}$ for transient or dynamic strain. If we compare these values with the safety criteria of Newmark, then it would appear that the estimated strain step is not likely to generate a damaging stress in the pipeline, but that the transient (dynamic) strain may be capable of generating dangerous stress levels.

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