1988 Saguenay earthquake and design of rigid underground walls for Southeastern Canada seismicity

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ABSTRACT

The classic Mononobe-Okabe formulation has been widely adopted in seismic design of retaining walls for several decades. Although the formulation has proved to be quite appropriate for retaining walls which experience an active yielding condition during ground shaking, it is suggested that the formulation would underestimate the induced dynamic soil pressure increment for rigid, non-yielding walls of underground structures. Based on the results of more recent analytical work by Wood (1973) and model wall tests undertaken at the Central Laboratories of New Zealand (Yong 1985; Elms and Wood 1987), alternate recommendations are proposed for the seismic design of rigid, non-yielding walls in southeastern Canada in the wake of the well documented 1988 Saguenay earthquake.

INTRODUCTION

The current practice of seismic design of rigid, non-yielding retaining walls of underground structures such as multi-level building basements, box-like transportation and hydraulic modules, monolithic bridge abutments, power plants, pumping stations, etc., generally uses the well-known Mononobe-Okabe (MO) formulation developed over 60 years ago, or a simplified version of it proposed by Seed and Whitman (1970) (MO-SW). Although the MO formulation has stood the test of time quite well for walls which yield adequately under ground shaking, it is often overlooked that the formulation would underestimate the earthquake induced soil pressure increments against rigid, non-yielding walls as described above, and may lead to unsafe designs. Accordingly, the same argument is also valid for the MO-SW formulation, which is given for a typical cohesionless soil backfill with horizontal surface as:

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$$\Delta P_{AE} = \frac{3}{8} K_h \gamma H^2 \qquad (1)$$

where ΔP_{AE} is dynamic force increment due soil/backfill, K_h g is horizontal ground acceleration at the base of wall, γ is unit weight of the soil, and H is height of soil/backfill against the wall.

SEISMICITY OF SE CANADA

For earthquake resistant design of buildings seismic risk in Canada has been prescribed by probabilistic strong ground motion maps in the National Building Code of Canada (NBCC). Background information on the progressive development of these maps, the methodology followed and the uncertainties involved were reported by Basham et al (1985). 32 earthquake source zones have been defined within the boundaries of Canada based on historical seismicity, regional seismotectonics and geology as understood by early 1980's. With this source model Cornell-McGuire method of probabilistic ground motion estimation was used to develop the maps in the Code (Basham et al. 1985; Basham 1987).

The earthquake source zones defined for the general region of southeastern Canada are shown in Fig. 1, including the subregions of Charlevoix (CHV), western Quebec (WBU), northern Appalachians (NA), Laurentian slope (LSP) and Lower St. Lawrence (LSL) (Basham et al. 1985). Charlevoix subregion has been the most active seismic source in eastern North America with five or six earthquakes of magnitude 6 or greater having occurred in 1638, 1663, 1791, 1860, 1870 and 1925 (Basham 1987). In the western Quebec subregion documented large seismic events have been the M6.2 Montreal earthquake of 1732, M6.2 Temiskaming earthquake of 1935 and the M5.6 Cornwall earthquake of 1944 (Adams and Basham 1987).

The 1985 NBCC includes a peak horizontal ground acceleration map and a peak horizontal ground velocity map with probability of exceedance of 10 percent in 50 years. The acceleration and velocity maps provide independent ground motion reference levels in the design of squatty rigid structures with shorter periods and tall flexible structures with longer periods, respectively (Basham et al. 1985; Ishiyama and Rainer 1987). Typical underground structures described earlier belong to the former group. The peak horizontal acceleration map for the portion of southeastern Canada is reproduced in Fig. 2 (Basham et al. 1985).

An earthquake of magnitude 6.0 occurred in the Saguenay region of the province of Quebec on 25 November 1988. It has been the largest earthquake in eastern North America since the 1935, M6.2 earthquake near Temiskaming, Quebec. The epicenter of the Saguenay earthquake, which is depicted with an encircled star in Fig. 3 was located at approximately 35 km south of the cities of Chicoutimi and Jonquiere and about 100 km northwest of the active Charlevoix earthquake zone. There has been no previously known significant earthquake activity in the Saguenay region. The focal depth of the earthquake was determined by Geological Survey of Canada at 29 km, twice as deep as compared to most of the eastern Canadian earthquakes previously studied (EERI 1989; Adams and Basham 1989).

The seismic activity generated by the Saguenay earthquake was recorded by the eastern Canadian strong-motion seismograph network shown in Fig. 3 (EERI 1989). All instruments were installed on bedrock except Baie-St. Paul. Accelerographs at 15 of the 22 sites triggered on the main shock of 25 November 1988. In Fig. 3 the triggered sites are depicted with solid circles and the maximum horizontal acceleration recorded in (g) by each instrument are given (Munro and Weichert 1989). The largest maximum horizontal acceleration, 0.174 g, was recorded at Baie-St. Paul on alluvium. The largest maximum horizontal acceleration on bedrock, 0.156 g, was measured at St. Andre. The seismic activity was also measured by the U.S. National Center of Earthquake Engineering Research strong-motion stations. The maximum horizontal acceleration of 0.09 g was recorded at Dickey, Maine about 200 km from the epicenter (EERI 1989).

Much of the damage caused by the Saguenay earthquake in the epicenter region and at distances of up to 350 km was due in whole or in part to soft subsoil conditions or to poor performance of unreinforced masonry (EERI 1989, EQE 1989). Amplification of rock motion through soft soil deposits was demonstrated at Baie-St. Paul and elsewhere. The lack of soft soils overlying the bedrock may account for the modest level of damage observed in the populated areas near the epicenter (EQE 1989).

DESIGN CRITERIA FOR NON-YIELDING RIGID WALLS

Design earthquake for the study

Based on an overall assessment of the peak horizontal ground acceleration zoning map for SE Canada (Fig. 2), and maximum horizontal ground accelerations recorded during the 1988 Saguenay earthquake (Fig. 3), a design horizontal ground acceleration of 0.16 g has been selected to be representative of the seismic risk in SE Canada within the context of this study. An exception has been made for the highly seismic Charlevoix subregion encircled by the 0.32 g contour in Fig. 3, for which a design horizontal ground acceleration of 0.32 g has been assigned.

Wood's analytical work

Wood (1973, 1975) considered the rigid, non-yielding retaining wall problem as depicted in Fig. 4. The soil/backfill is assumed to be homogeneous, isotropic and elastic. A uniform body force field is considered representative of the earthquake induced inertia forces on the soil. The lower boundary consists of competent ground along which no soil displacement occurs. Wood (1973), utilized the finite element technique and obtained static elastic solutions for the dynamic soil pressure increments against the rigid, non-yielding wall. Solutions for the case of the soil shear modulus increasing linearly with depth have been generated by the author for a horizontal acceleration of 0.16 g in Fig. 5. The actual value of the modulus does not affect the results. The solutions indicate the significant influence of the problem geometry defined by the L/H ratio. The pressure distribution is capped by the passive pressure envelope for the particular soil.

Elastic solutions in close agreement with Wood's (1973) were also obtained by Scott (1973) who used a one-dimensional shear beam analogy to model the soil retained by the rigid non-yielding wall, as demonstrated by Soydemir (1991).

In Fig. 6, the dynamic force increment calculated both by Wood's (1973) model, and the MO-SW formulation for a horizontal ground acceleration of 0.16 g, are presented for comparison. It is observed that the dynamic thrust on rigid, non-yielding walls may be underestimated by about 2.5 times by the MO-SW formulation. Whitman (1990) has also drawn attention to this condition.

Model tests by the Central Laboratories of New Zealand

Since the early 1980's, a comprehensive model testing program has been undertaken at the Central Laboratories, Ministry of Works and Development in New Zealand (CLNZ) to study the dynamic and static earth pressure increments on non-yielding and forced-displaced rigid walls (Elms and Wood 1987). A large number of tests for model retaining walls built on a shaking table have been performed (Yong 1985) to provide experimental data to assess the validity of the Wood's (1973) analytical results which had been the basis in developing recommendations for seismic design practice in New Zealand (Matthewson et al. 1980).

Results of Yong's (1985) tests for a non-yielding rigid model wall are summarized in Fig. 7, which depicts the measured maximum dynamic force increments by a cohesionless soil backfill as a function of the applied horizontal base acceleration. Dynamic force increments calculated from Wood's (1973) analytical solutions are included in the figure for comparison. The author has also incorporated in the figure the force increments calculated using the MO-SW formulation. It is observed that the experimental results are in close agreement with Wood's (1973) analytical solutions, however, they are significantly greater than the dynamic force increments given by the MO-SW formulation.

<u>Recommendations for SE Canada</u>

Based on the results of analytical and experimental works presented above, it is proposed that recommendations provided in Fig. 8 be adopted in seismic design practice of rigid, non-yielding retaining walls in SE Canada. Dynamic soil pressure increments in Fig. 8 correspond to a horizontal ground acceleration of 0.16 g and are believed to be applicable to the region in general. For the highly seismic Charlevoix subregion, as defined earlier, the pressure increments in Fig. 8 should be multiplied by two in compliance with the 0.32 g design horizontal ground acceleration selected for the subregion. Linear proportionality is acceptable since the soil is assumed to be elastic in Wood's (1973) solutions. Fig. 8 also includes the dynamic soil pressure increments calculated from the MO-SW formulation for comparison, and the criteria currently used in New Zealand design practice (NZP) for the regions represented by a horizontal ground acceleration level of 0.16 g.

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REFERENCES

Adams, J. and Basham, P.W. 1987. Seismicity, crustal stresses and seismotectonics of eastern Canada. Natl. Cent. Earthquake Engr. Res., Tech. Rept. NCEER-87-0025, 127-142.

Adams, J. and Basham, P.W. 1989. Implications of the 1988 Saguenay earthquake for seismic hazard zoning of southeastern Canada. Eastern Sect. Seism. Soc. Am., Seism. Res. Let., 60(1).

Basham, P.W., Weichert, D.H., Anglin, F.M. and Berry, M.J. 1985. New probabilistic strong seismic ground motion maps of Canada. Bull. Seism. Soc. Am., 75(2), 563-595.
Basham, P.W. 1987. Seismic hazards assessment and seismic codes for eastern Canada. Natl. Cent. Earthquake Engr. Res., Tech. Rept. NCEER-87-0025, 1-15.
EERI. 1989. The Saguenay, Quebec, Canada, earthquake of 25 November 1988. EERI Newslet., 23(5).
Elms, D.G. and Wood, J.H. 1987. Earthquake induced displacements and pressures on retaining walls and bridge abutments. Proceed. New Zealand Roading Symp., 4, 809-820.
EQE Engr. 1988. The Saguenay earthquake of November 25, 1988, a preliminary summary, San. Fran., CA.
Ishiyama, Y. and Rainer, J.H. 1987. Comparison of seismic provisions of 1985 NBC of Canada, BSC of Japan and 1985 NEHRP of the USA. Proceed. 5th Can. Conf. Earthquake Engr., 747-756.
Matthewson, M.B., Wood, J.H., and Berrill, J.B. 1980. Seismic design of bridges - earth retaining structures. Bull. New Zealand Soc. Earthquake Engr., 13(3), 280-293.
Munro, P.S. and Weichert, D. 1989. The Saguenay earthquake of Nov. 25, 1988 - processed strong-motion records. Geol. Surv. Can., Open File Rept. No. 1996.
Seed, H.B. and Whitman, R.V. 1970. Design of earth retaining structures for dynamic loads. Proceed. ASCE Spec. Conf. Cornell Univ., 817-842.
Soydemir, C. 1991. Seismic design of rigid underground walls in New England. Proceed. 2nd Intl. Conf. Geotech. Earthquake Engr. Soil Dynamics, St. Louis, Missouri.
Whitman, R.V. 1990. Seismic design and behavior of gravity retaining walls. Proceed. ASCE Conf. Design Perform. Earth Retain. Struct., Cornell Univ., 817-842.
Wood, J.H. 1973. Earthquake-induced soil pressures on structures. Earthquake Engr. Res. Lab., Calif. Inst. Tech., Rept. EERL 73-05.
Wood, J.H. 1975. Earthquake induced pressures on rigid wall structure. Bull. New Zealand Soc. Earthquake Engr. 8(3), 175-186.
Yong, P.M.F. 1985. Dynamic earth pressures against a rigid earth retaining wall. Central Lab., Min. Works and Devel., New Zealand, Rept. 5-85/5.

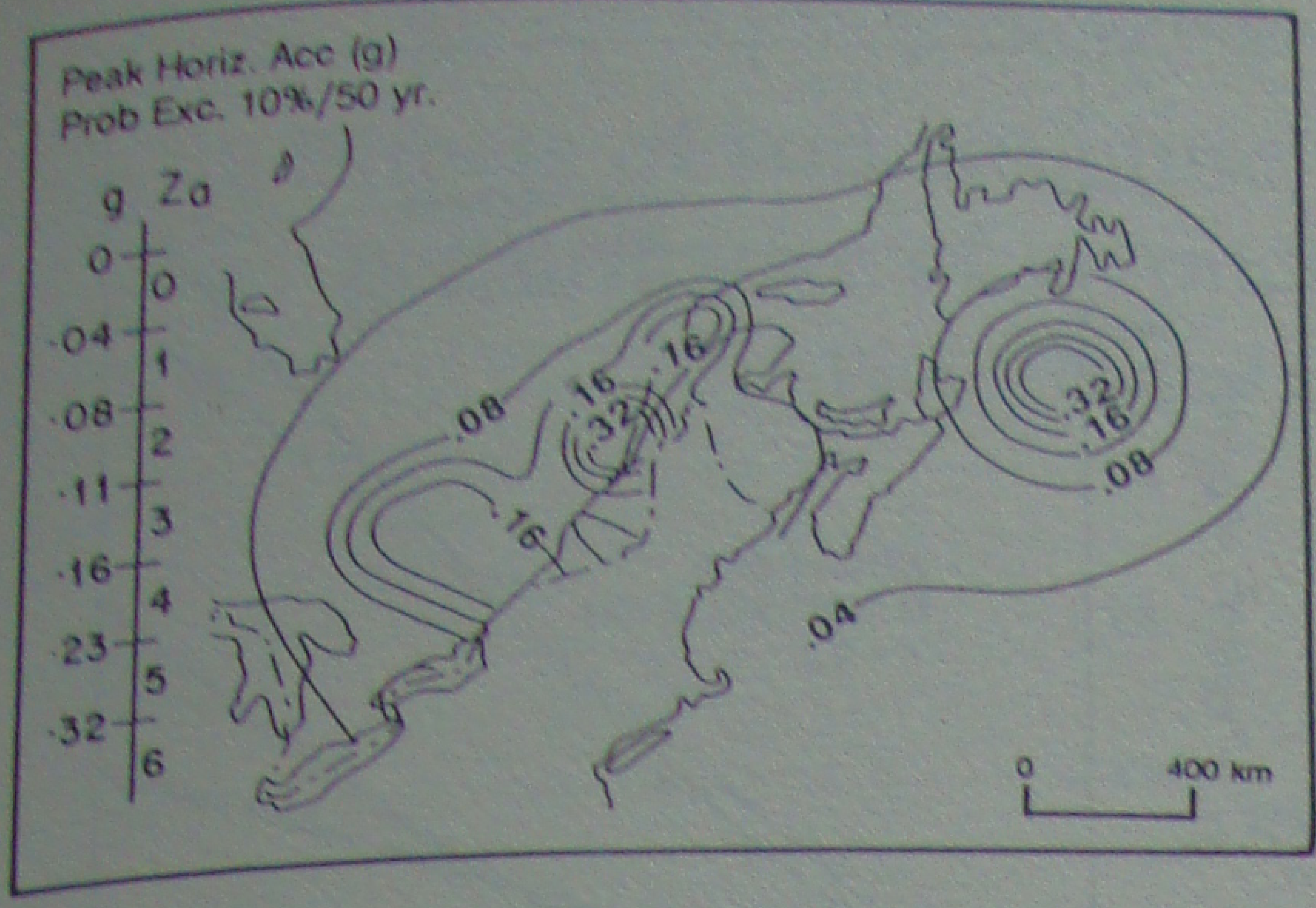

Figure 1. Earthquake source zones in SE Canada (Basham et al. 1985)

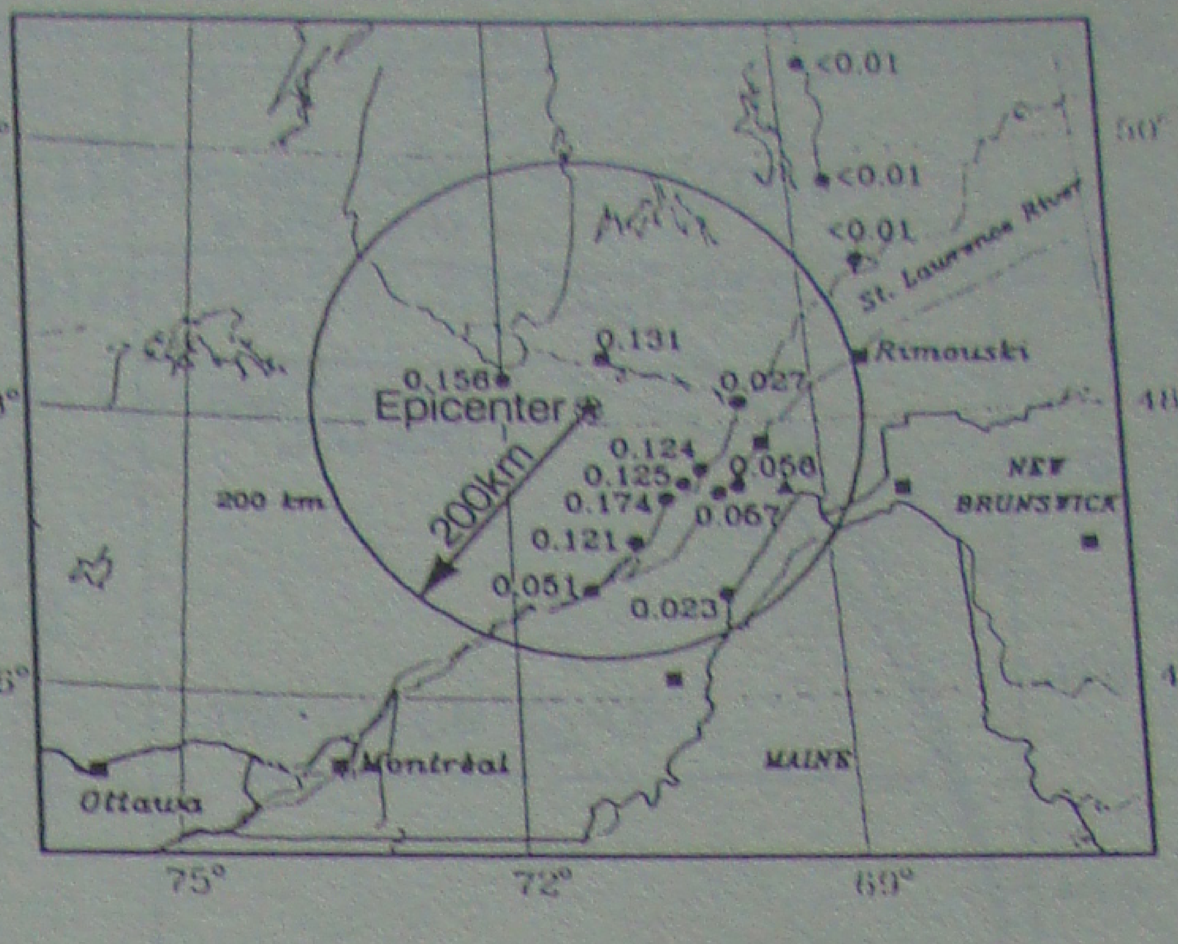

Figure 3. Maximum horizontal ground acceleration in (g), Saguenay, 25 Nov. 1988 (Munro and Weichert 1989; EERI 1989)

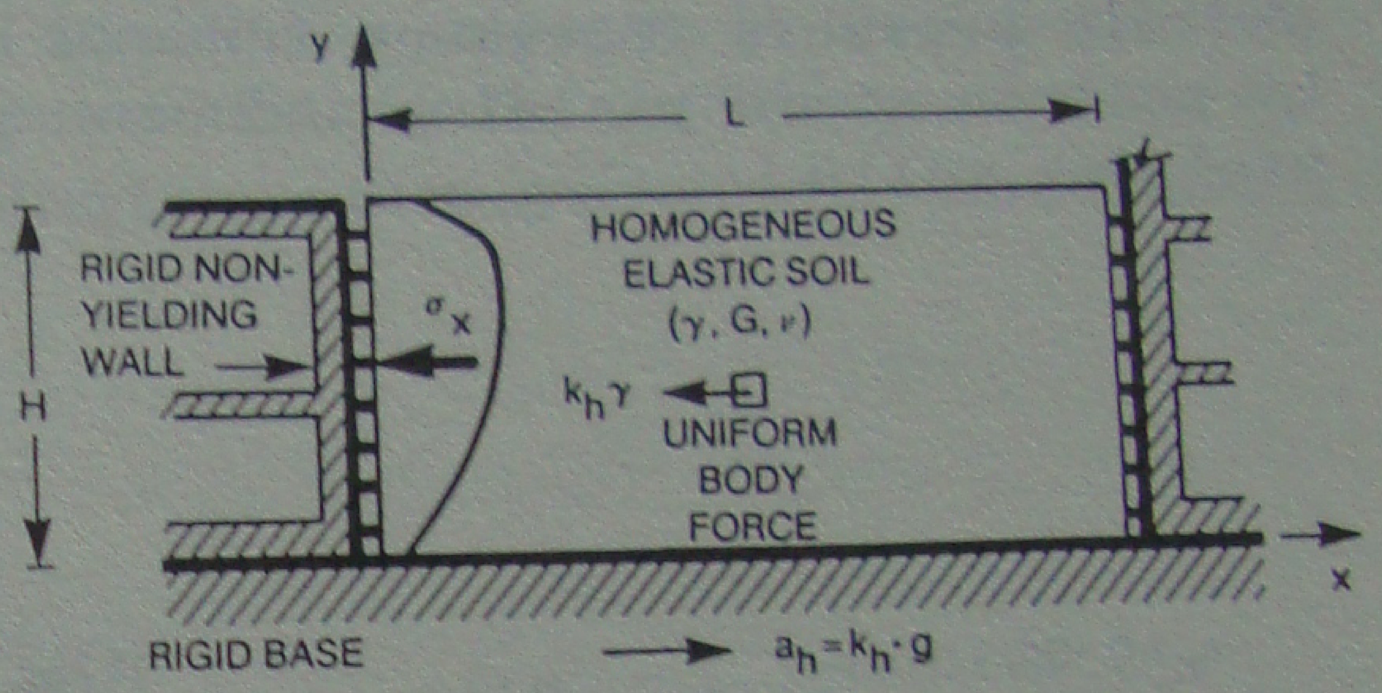

Figure 4. Wood's (1973) analytical problem

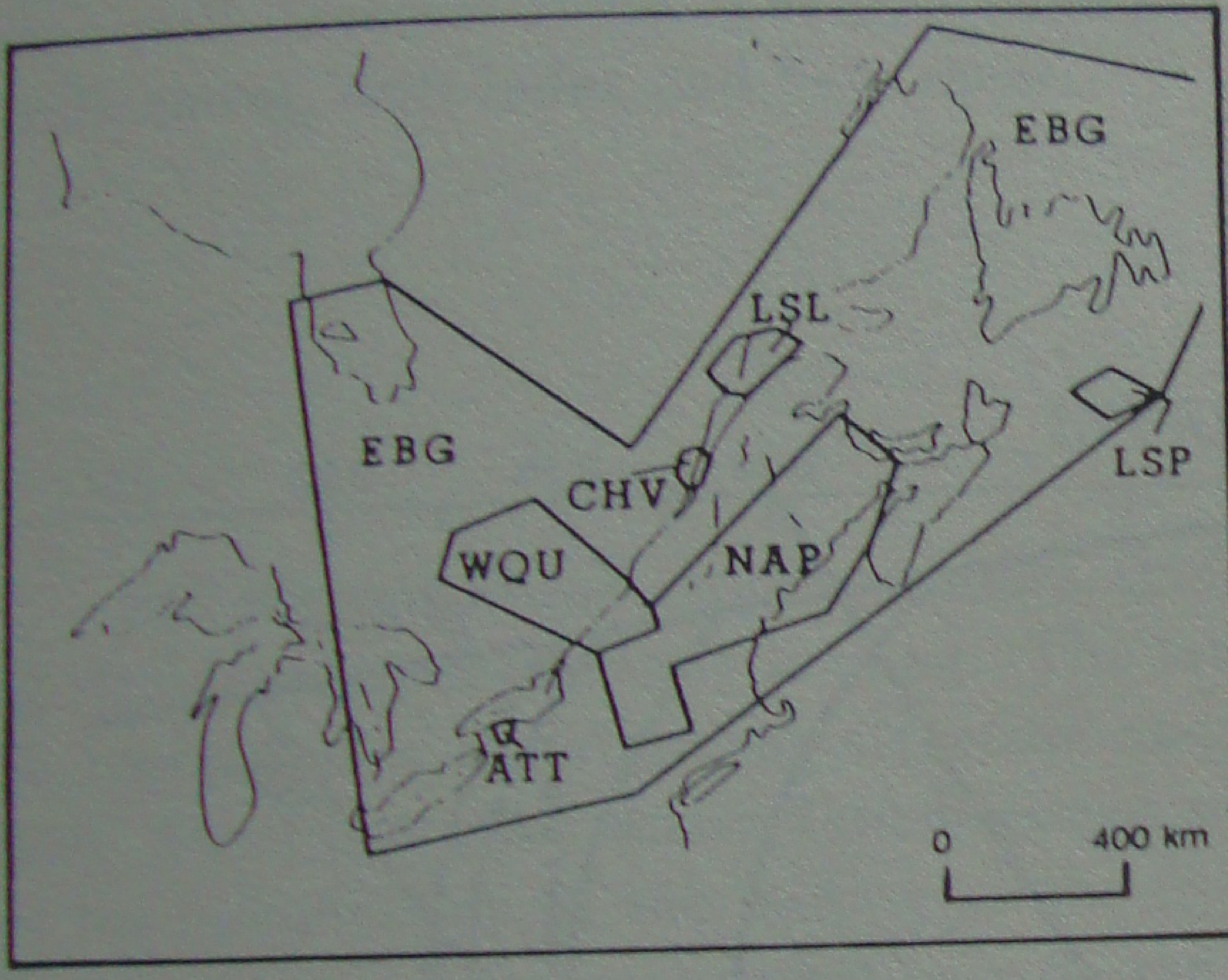

Figure 2. Peak horizontal acceleration zoning map for SE Canada (Basham et al. 1985)

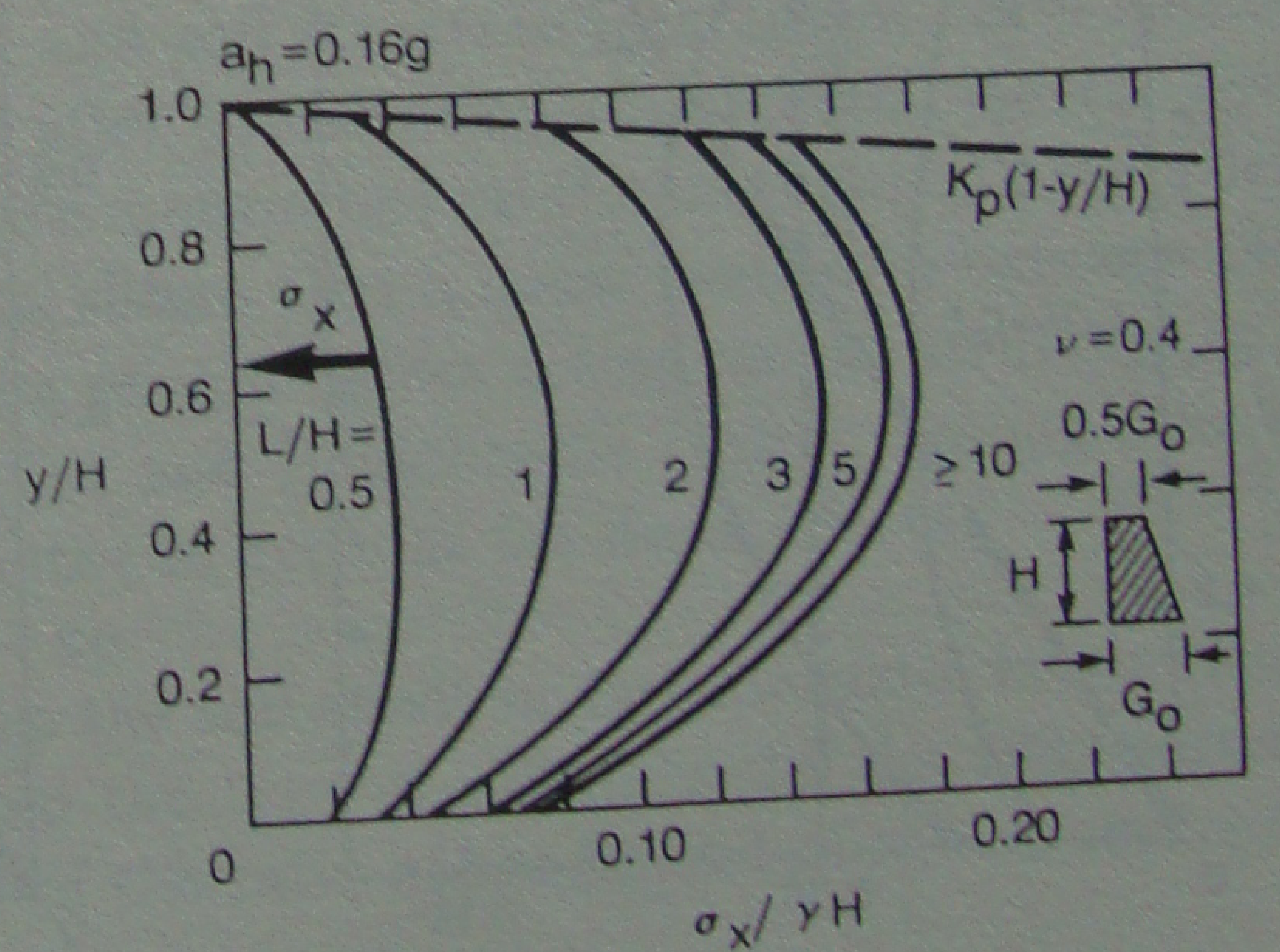

Figure 5. Seismic soil pressure increments on rigid non-yielding wall for $a_h = 0.16 \cdot g$ by Wood's (1973) solution

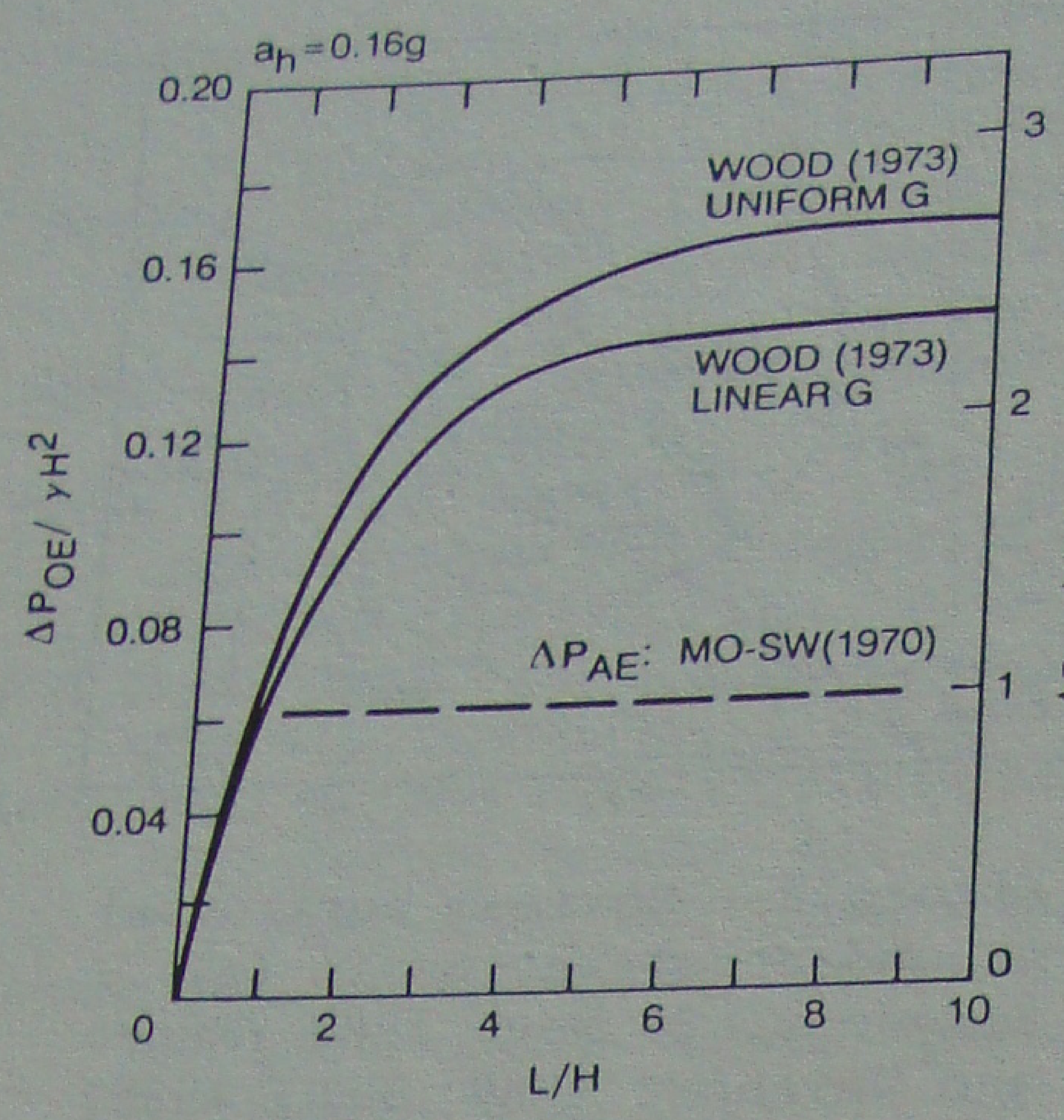

Figure 6. Analytical results for seismic pressure increment induced by soil on rigid yielding and non-yielding walls

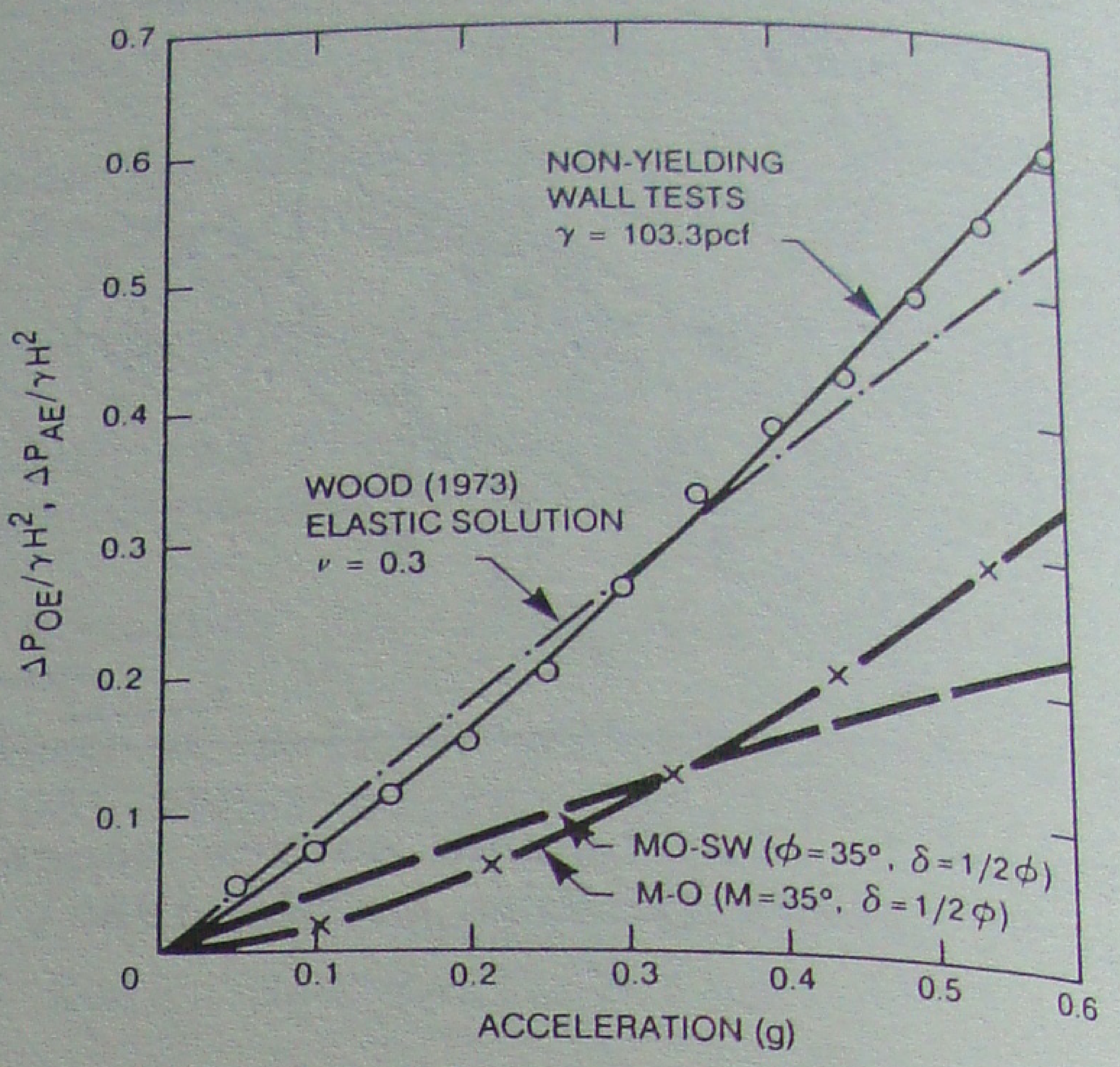

Figure 7. Dynamic soil pressures on yielding and non-yielding walls (after Yong 1985, Elms and Wood 1987)

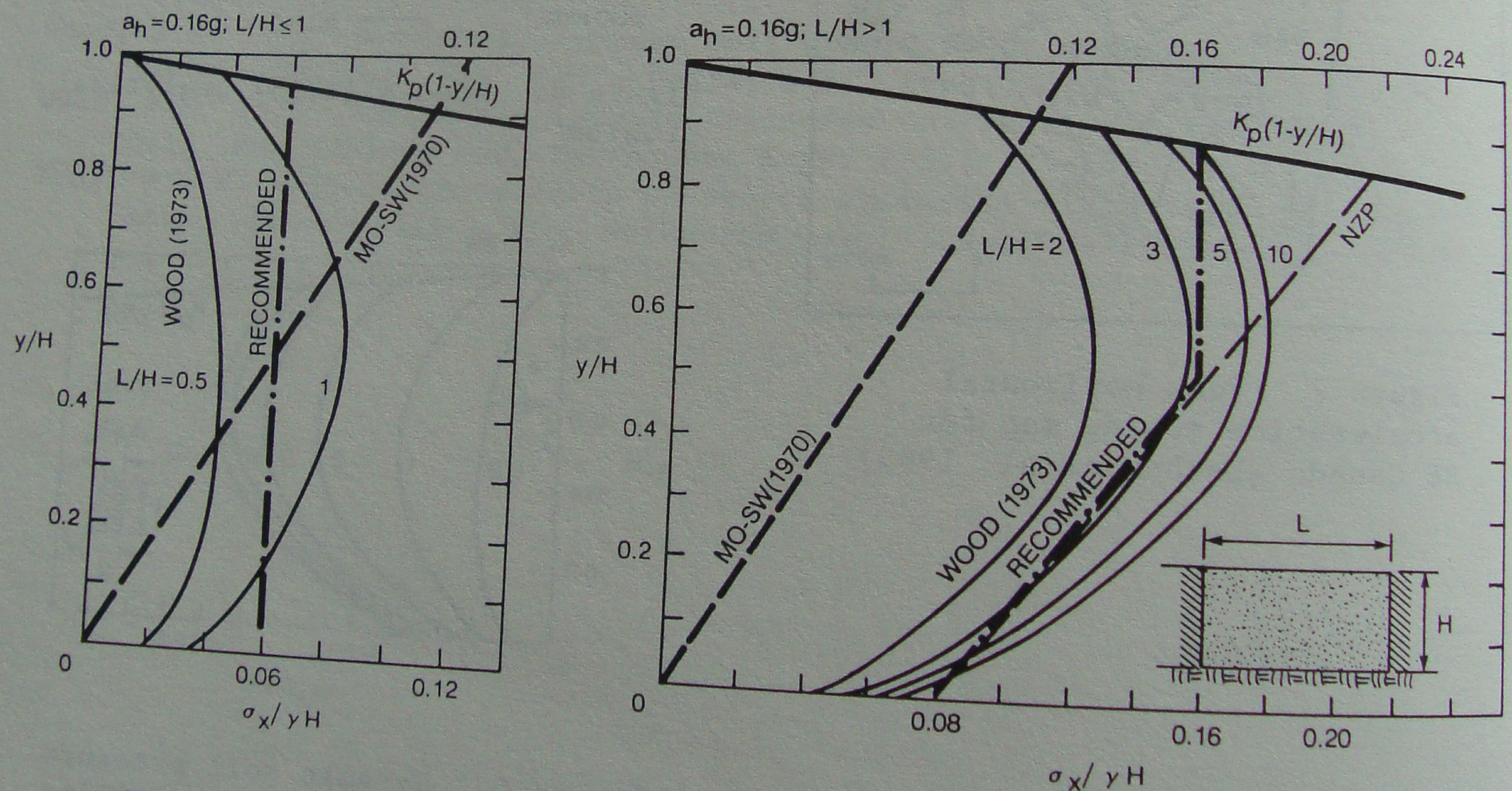

Figure 8. Recommended seismic soil pressure increment against rigid non-yielding walls in SE Canada