ENERCON SERVICES, INC.	CALCULATION COVER SHEET	CALC. NO. : TXUT-001-FSAR-2.5-CALC-010			
		REV.	4		
		PAGE NO.	1	Of	41
Title:	Lateral Earth Pressures	Client: MNES			
		Project: MITS194			

Item	Cover Sheet Items	Yes	No
1	Does this calculation contain any assumptions that require confirmation? (If **YES**, Identify the assumptions) ____________		X
2	Does this calculation serve as an "Alternate Calculation"? (If **YES**, Identify the design verified calculation.) **Design Verified Calculation No.**____________		X
3	Does this calculation Supersede an existing Calculation? (If **YES**, identify the superseded calculation.) **Superseded Calculation No.**____________		X

Scope of Revision:

Figures 1 and 2 updated to show the latest plant layout and yard grade.

Pages 7, 8, 10, 11, 12, 13, 14 and 26 are updated with some editorial changes incorporating updated plant layout and updated and new references.

Revision Impact on Results:

None.

Preliminary Calculation	☐	**Final Calculation**	X
Safety-Related	X	**Non-Safety Related**	☐

(Print Name and Sign)

Originator(s): Osman El Menchawi [signature]	**Date: 9-16-13**
Design Verifier: Kathy Reyes [signature]	**Date: 9-16-13**
Approver: Joseph Mancinelli, Project Manager [signature]	**Date: 9-16-13**

CALCULATION REVISION STATUS

REVISION	DATE	DESCRIPTION
0	08-05-08	Initial Issuance of Calculation Package.
1	09-03-09	Sections 6.3.1, 6.3.2, and 7.0 are revised.
2	08-25-11	Sections 3.0, 4.0, 5.0, 6.0, and 7.00 are revised.
3	12-01-11	Section 5.4.4, and Figures 9b and 10b are updated to include an effective ground acceleration coefficient that is equal to the design PGA value. Figure 1 is updated to show the latest plant layout. Pages 8, 9, 10, 11, and 13 are updated with some editorial changes.
4	09-16-13	Sections 3.0, 4.0, 5.0, and 6.0 are revised. Figures 1 and 2 updated to show the latest plant layout.

PAGE REVISION STATUS

PAGE NO.	REVISION	PAGE NO.	REVISION
1-41	4		

APPENDIX REVISION STATUS

APPENDIX NO.	PAGE NO.	REVISION NO.	APPENDIX NO.	PAGE NO.	REVISION NO.

Calculation Design Verification Plan:

1. Apply CSP 3.01 Rev. 6 Section 4.5a (Design Review Method)

2. Check the revised Sections 3.0 to 6.0 and all figures to ensure consistency.

(Print Name and Sign)

Approver: Joseph Mancinelli, Project Manager [signature]	**Date: 9-16-13**

Calculation Design Verification Summary:

1. Compared documented input with the source reference and checked validity of reference for intended use.
2. Evaluated and verified assumptions to determine that they were based on sound engineering practices and principles.
3. Checked the revised Sections 3.0 to 6.0 and all figures to ensure consistency.

Based On The Above Summary, The Calculation Is Determined To Be Acceptable.

(Print Name and Sign)

Design Verifier: Kathy Reyes [signature]	**Date: 9-16-13**
Others:	**Date:**

Item	Checklist Items	Yes	No	N/A
1	**Design Inputs** - Were the design inputs correctly selected, referenced (latest revision), consistent with the design basis and incorporated in the calculation?	X		
2	**Assumptions** – Were the assumptions reasonable and adequately described, justified and/or verified, and documented?	X		
3	**Quality Assurance** – Were the appropriate QA classification and requirements assigned to the calculation?	X		
4	**Codes, Standard and Regulatory Requirements** – Were the applicable codes, standards and regulatory requirements, including issue and addenda, properly identified and their requirements satisfied?			X
5	**Construction and Operating Experience** – Have applicable construction and operating experience been considered?			X
6	**Interfaces** – Have the design interface requirements been satisfied, including interactions with other calculations?	X		
7	**Methods** – Was the calculation methodology appropriate and properly applied to satisfy the calculation objective?	X		
8	**Design Outputs** – Was the conclusion of the calculation clearly stated, did it correspond directly with the objectives and are the results reasonable compared to the inputs?	X		
9	**Radiation Exposure** – Has the calculation properly considered radiation exposure to the public and plant personnel?			X
10	**Acceptance Criteria** – Are the acceptance criteria incorporated in the calculation sufficient to allow verification that the design requirements have been satisfactorily accomplished?			X
11	**Computer Software** – Is a computer program or software used, and if so, are the requirements of CSP 3.02 met?			X

COMMENTS:

(Print Name and Sign)

Design Verifier: Kathy Reyes [signature]	**Date: 9-16-13**
Others:	**Date:**

COMANCHE PEAK COMBINED OPERATING LICENSE APPLICATION
Calculation Package TXUT-001-FSAR-2.5-CALC-010
LATERAL EARTH PRESSURES

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1.0 PURPOSE AND SCOPE

This calculation package summarizes geotechnical recommendations and input to retaining walls and foundation lateral earth pressure estimates for the proposed seismic category I and II structures for Units 3 and 4 at the Comanche Peak Nuclear Power Plant (CPNPP), for the Combined Operating License Application (COLA).

2.0 SUMMARY OF RESULTS AND CONCLUSIONS

This document provides geotechnical considerations, evaluation and recommendations for lateral earth pressure design for the CPNPP Units 3 and 4 seismic category I and II structures. Design recommendations are provided in Section 6.0. Sample calculations for lateral earth pressures are provided in Section 7.0.

3.0 REFERENCES

3.1 Project References

3.1.1 Mitsubishi Heavy Industries (2012), Grading and Drainage Plan, Document No. 4CS-CP34-20080060, Rev. 4, Final, dated 12-09-12.

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3.1.4 Mitsubishi Heavy Industries (2013), R/B Complex Foundation Overturning Stability, Document No. N0-EF00U04, Rev. 1, dated 9-6-13.

3.1.5 Fugro Consultants, Inc. (2013), Dynamic Profile, Project Report No. TXUT-001-PR-007 Rev. 9.

3.1.6 Fugro Consultants, Inc. (formerly William Lettis and Associates, Inc.) (2007), Engineering Stratigraphy, Calculation Package No. TXUT-001-FSAR-2.5-CALC-004, Rev. 0.

3.1.7 Fugro West, Inc. (2008), Laboratory Test Data Report, Project Report No. TXUT-001-PR-010, Rev. 0.

3.1.8 Mitsubishi Heavy Industries (2013), Site Specific Structural Design of US-APWR Ultimate Heat Sink Related Structure – SSI-12-05-100-009, Document No. 4DS-CP34-20080052, Rev. 4, dated 8-6-13.

3.1.9 Mitsubishi Heavy Industries (2013), Site Specific Structural Design of US-APWR ESWPT – SSI-12-05-100-007, Document No. 4DS-CP34-20080054, Rev. 4, dated 7-26-13.

3.1.10 Mitsubishi Heavy Industries (2013), Site Specific Structural Design of US-APWR PSFSV – SSI-12-05-100-005, Document No. 4DS-CP34-20080056, Rev. 4, dated 7-30-13.

3.1.11 Enercon Services, Inc. (2012), Evaluation of Maximum Post-Construction Groundwater Level, Calculation No. TXUT-001-FSAR-2.4.12-CALC-038, Rev. 2.

3.1.12 Fugro Consultants, Inc. (2013), Coefficients of Sliding and Sidewall Friction, Calculation No. TXUT-001-FSAR-2.5-CALC-041, Rev. 0.

3.1.13 Fugro Consultants Inc. (2013), Documentation of Smooth Horizontal and Vertical GMRS and FIRS for Comanche Peak Units 3 and 4, FCL QA record 0737-ACR-040, Rev. 7.

3.2 General References

3.2.1 Duncan, J.M., Williams, G.W., Sehn, A.L., Seed, R.B., (1991), Estimation Earth Pressures Due to Compaction, Journal of the Geotechnical Engineering Division, ASCE, Vol. 117, GT12, December 1991.

3.2.2 Duncan, J.M., Williams, G.W., Sehn, A.L., Seed, R.B., (1993), Closure of Estimation Earth Pressures Due to Compaction, Journal of the Geotechnical Engineering Division, ASCE, Vol. 119, pg 1172, 1993.

3.2.3 Ingold, T.S., (1979), Retaining Wall Performance During Backfilling, Journal of the Geotechnical Engineering Division, ASCE, Vol. 105, GT5, May 1979.

3.2.4 Kramer, S.L. (1996), Geotechnical Earthquake Engineering, Prentice-Hall, New Jersey.

3.2.5 Naval Facilities Engineering Command (NAVFAC) (1986), Foundations & Earth Structures, Design Manual 7.02, dated September 1986.

3.2.6 Seed, H.B., and Whitman, R.V. (1970), Design of Earth Retaining Structures for Dynamic Loads, ASCE Specialty Conference on Lateral Stresses in the Ground and Design of Earth Retaining Structures, Ithaca, New York.

3.2.7 Winterkorn, H.F., Fang, H. (1975), Foundation Engineering Handbook, Van Nostrand Reinhold Company, New York.

3.2.8 Wood, J.H. (1973), Earthquake Induced Soil Pressures on Structures, Doctoral Dissertation, EERL 73-05, California Institute of Technology, Pasadena, CA.

4.0 ASSUMPTIONS

The following is a list of assumptions that were made as part of preparation of this calculation package:

- All foundations for seismic category I and II structures are assumed to be of mat type foundation founded on or embedded in competent Layer C limestone or on fill concrete.

- All below-grade structure walls are assumed to be unyielding (wall cannot rotate), implying at-rest earth pressure conditions. The backfill surface for all unyielding walls is assumed to be horizontal.
- The retaining walls planned along the northeast and northwest boundaries of the site are assumed to be yielding (wall can rotate), which implies active earth pressure conditions.
- Rankine and Coulomb earth pressure theories are utilized. All walls are assumed to be vertical with no shear forces present on the back face. All pressures and resultant forces are assumed to be horizontal. It is also assumed that sufficient wall movement can occur so that shear strength on rupture surface is completely mobilized.
- Surcharge loads are assumed to be uniform.
- Effect of vertical ground acceleration coefficient is assumed to be negligible and is not considered.

5.0 DESIGN INPUT

The following paragraphs provide a summary of the data and information with respect to the plant structures, site grading, and subsurface materials properties utilized in preparing this report.

5.1 General Plant Information

The CPNPP structures of each unit consist of the Reactor Building (R/B), Auxiliary Building (A/B), East Power Source Building (EPS/B), and West Power Source Building (WPS/B) all of which share the same foundation mat forming the Reactor Building Complex (R/B Complex). The other structures consist of the Power Source Fuel Storage Vault (PSFSV), Essential Service Water Pipe Tunnel (ESWPT), Ultimate Heat Sink Related Structures (UHSRS), Turbine Building (T/B), and Turbine Generator Pedestal (T/G). There are no seismic category I Duct Banks. The preliminary general plant arrangement showing the layout and plan dimensions of the main structures, foundation loadings, and basement embedment depths have been provided for the proposed CPNPP Units 3 and 4 by Mitsubishi Heavy Industries (MHI) (Refs. 3.1.1 through 3.1.4 and 3.1.8 through 3.1.10). All seismic category I and II structures will be founded on or embedded in the competent Layer C limestone which is at an average elevation of approximately 782 ft or on fill concrete which extends from the foundation bottom to the top of solid limestone at an average elevation of 782 ft. If the foundation bottom elevation is higher than the top of Layer C limestone, the current design requires that all of the materials above the Layer C limestone be removed and replaced with fill concrete.

Table 5.1-1 provides a summary of the pertinent data for the primary seismic category I and II structures within each unit:

Table 5.1-1 Main Seismic Category I & II Structures' Details

Building	Category	Foundation Length (ft)		Foundation Bottom Elev. (ft)	Fill Concrete Thickness below Foundations (ft)	Subgrade Below Foundations
		E-W	N-S			
R/B Complex	I	347	334.58	779.75	~0	Fill Concrete over Limestone
T/B	II	265.5	342.67	794.83	~ 12.83	Fill Concrete over Limestone
T/G	II	62.33	233.42	786.83	~4.83	Fill Concrete over Limestone
PSFSV	I	98	95	782	~ 0	Fill Concrete over Limestone
UHSRS	I	267	160	786	~ 4	Fill Concrete over Limestone
ESWPT	I	26 (Tunnel Width)		791.08	~ 9.08	Fill Concrete over Limestone

Based on the finish grade elevation of 822 ft and the above information, the below grade portions of the seismic category I and II structures would range between about 27.17 and 42.25 ft, with the exception of the pump house within the UHSRS basin that extends to 48 ft.

5.2 Site Grading

Based on the site grading plans provided by MHI (Ref. 3.1.1), the final finish grade for the main plant area will be at elevation 822 ft. The present existing grades vary between El. 830 and 855 ft within the Unit 3 main plant area and between El. 842 and 868 ft within the Unit 4 main plant area. Therefore, the approximate cuts range from 11 to 36 ft for Unit 3 and about 23 to 49 ft for Unit 4 main plant areas. There are also two fill slope areas planned along the northwest and northeast periphery of the site where the Heat Sinks are located. The fill along the northwest corner of the Unit 4 Heat Sinks ranges up to about 21 ft of new fill over an existing 4H:1V (Horizontal:Vertical) slope and the fill along the northeast corner of Unit 3 Heat Sinks ranges to up to about 36 ft of new fill over an existing 7H:1V slope. The northern and western perimeter of the site is predominantly bounded by about 5-ft tall barriers or retaining walls that range in height from 7 ft to about 37 ft.

5.3 Layer B Shale Removal and Fill Concrete

Table 5.1-1 indicates that foundation bottom elevations for seismic category I and II structures range between about elevations 779.75 and 794.83 ft. This foundation elevation ranges generally fall within the Layers B and C materials (see Table 5.4.2-1 below). Due to anticipated undesirable potential shrink/swell properties, Layer B shale material below the foundations will be removed to the top of the Layer C limestone rock at an average elevation of 782 ft. Any overexcavations below the foundations will be backfilled with fill concrete to the foundation bottoms.

5.4 Site Conditions and Background Data

5.4.1 Site Exploration

Field exploration and sample collection for the CPNPP project was performed between November 2006 and April 2007. The field exploration phase included 161 boreholes, ranging from 40 to 550 ft deep, and 3 test pits up to 20 ft deep that were excavated, logged and sampled (Figure 1). Logging was performed by Fugro Consultants, Inc. (formerly William Lettis and Associates, Inc. (WLA)). Geotechnical laboratory testing associated with the field work was performed between March 2007 and November 2007 primarily at the Fugro Laboratory in Houston, Texas.

5.4.2 Subsurface Conditions

Subsurface materials within the project site consist of three main geologic formations in descending order: Glen Rose Formation, Twin Mountain Formation, and Mineral Wells Formation. The Glen Rose Formation consists primarily of limestone with interbedded layers of claystone and shale, and is generally overlain by a layer of fill or residual soils, which varies in thickness from a few feet to a few tens of feet. Boring log and geophysical data further aided in refining the subsurface into twelve interpreted major stratigraphic layers labeled A through I. Figure 2 shows a typical geologic cross section for the main site of Units 3 and 4. A summary of the refined stratigraphic layers for the site is provided in Table 5.4.2-1. More detailed information and data regarding the project subsurface materials and stratigraphic layers are provided in the Project documents TXUT-001-PR-007 and TXUT-001-FSAR-2.5-CALC-004 (Refs. 3.1.5 and 3.1.6).

Residual soil material types ranged from sand and gravel with varying amounts of fines, to silt, and lean sandy clay. Some areas of the site (northeast of Unit 4 and east to southeast of Unit 3) contain areas of randomly placed, uncontrolled fill. These fill materials are located in areas of previous topographic lows and range in thickness from 5 to about 70 ft deep.

Table 5.4.2-1 Stratigraphic Layer Depth Profile

Formation	Stratigraphic Layers	Primary Lithology	Top of Layer Average Elevation (feet)	Average Thickness (feet)
Glen Rose	A	Limestone	834	35
	B1	Shale	798	8
	B2	Shale with Limestone interbeds	790	8
	C	Limestone	782	65
	D	Shale	717	4
	E1	Limestone	714	23
	E2	Limestone	690	35
	E3	Limestone	656	33
Twin Mountains	F	Limestone with Shale and Sand interbeds	622	30
	G	Sandstone	593	80
	H	Shale	513	63
	I	Sandstone	451	67
Mineral Wells	MW	Shale with Sandstone and Limestone interbeds	388	--

All existing residual soils and uncontrolled fill materials within the vicinity of the seismic category I and II structures will be removed as part of the site grading or foundation excavations. All materials bearing laterally in the immediate vicinity of the below grade structures and retaining walls are anticipated to consist of compacted fill.

5.4.3 Groundwater Conditions

The subsurface native soils and much of the rock, especially the Glen Rose Formation, are considered relatively impermeable and watertight. However, monitoring well data from onsite piezometers indicate the presence of some localized perched water at shallower elevations. Based on the general data available, the permanent groundwater level at the site is expected to occur deep in the rock mass below plant grade and foundation subgrade elevations. Based on theoretical maximum precipitation events, the maximum groundwater level calculated in Ref. 3.1.11 around the nuclear island is 794.94 ft msl. The areas of Units 3 and 4 within the ESWPT is essentially a closed basin which had not been included in the model area in Ref. 3.1.11. The pipe tunnels enclose this area, with the tops of individual segments of the pipe tunnels ranging from 804 ft msl to 810 ft msl. Because this is a closed area, the water level within this area can theoretically reach a maximum of 804 ft msl; once it has reached this elevation, the water will drain outward across those portions of the pipe tunnel having tops at that elevation.

5.4.4 Seismic Loading

The results of the ground motion and site response analyses performed for CPNPP Units 3 and 4 sites indicate that the horizontal peak ground acceleration (PGA) ranges between 0.046g and 0.077g (Ref. 3.1.13). Therefore, the minimum PGA of 0.1g was used as the design value for the horizontal PGA (Ref. 3.1.13). Because the PGA occurs for only one instant during an earthquake and does not have sufficient duration to cause significant wall displacement, the effective ground acceleration, developed a number of times during the earthquake will be somewhat less than the maximum. A reasonable estimate for the effective ground acceleration coefficient (k_h) that may tend to cause wall movements is about 85% of the peak ground acceleration (Ref. 3.2.6). However, for lateral earth pressure calculations provided herein, effective ground acceleration coefficient is conservatively assumed to be equal to the design PGA value.

5.5 Geotechnical Material Properties

5.5.1 Existing On-Site Materials

Generally, as shown on Figure 2, subsurface conditions consist of fairly shallow thicknesses of soil underlain by alternating layers of limestone, shale, and sandstone. The geotechnical properties and parameters for the existing subsurface materials are provided in the Laboratory Test Data Report (Ref. 3.1.7).

5.5.2 Compacted Fill

Compacted fill will be predominantly used for backfilling against all below grade portions of seismic category I and II structures and any retaining walls planned within the main plant area.

5.5.2.1 Proposed Fill Specification

Fill soils for construction of compacted fill shall conform to the following properties:

- Should consist of durable materials free from organic matter and any other deleterious or perishable substances, and shall be of such nature that it can be compacted readily under moisture conditioning and rolling to a firm and non-yielding state.
- Should be granular in nature with a well-graded grain size distribution and less than 30 percent fines fraction (percent passing No. 200 sieve, per ASTM D422 and D1140),
- Should not contain particles greater than 3 inches in the maximum dimension, with less than 15 percent by weight larger than 2.5 inches,
- Should have an expansion index (per ASTM D4829) of less than 20. Material with an expansion index greater than 20 is deemed to be expansive and is not acceptable, and
- Should have a liquid limit less than 40 percent and a plasticity index not exceeding 12 (per ASTM D4318).

In general, all compacted fills shall be placed in lifts no thicker than 8 inches (measured in loose state); moisture conditioned to within 2 percent of the optimum moisture content and compacted to a minimum relative compaction of 95 percent per ASTM D1557.

5.5.2.2 Compacted Fill Soil Design Parameters

Based on the specification requirements provided in Section 5.5.2.1, the geotechnical properties for the compacted granular fill materials are estimated as follow:

- Total Unit Weight (γ_t) ~ 125 pcf
- Internal Effective Friction Angle (ϕ') ~ 32°
- Effective Cohesion Intercept ~ 0-200 psf

Select backfill materials may be imported or obtained from onsite excavated materials that satisfy these assumed properties, although onsite materials will have to be processed, which may include selective grading, crushing, and stockpiling. Tests will have to be performed on stockpiled materials or imports to assess suitability as backfill material and verify the minimum assumed properties.

6.0 METHODOLOGY

6.1 Lateral Earth Pressures

Lateral earth pressures are a function of wall yielding, backfill geometry and characteristics, water, surcharge and earthquake loads. All seismic category I and II below-grade structure walls are assumed to be unyielding (restrained from displacement and rotation), which implies at-rest earth pressure conditions. The retaining walls planned along the northeast and northwest boundaries of the site are assumed to be yielding (free to displace at the top and rotate), implying active earth pressure conditions. All design recommendations are based on the assumptions of vertical retaining walls.

6.2 Lateral Static Pressures

Contributions to static lateral earth pressure are shown in Figure 3 and include backfill, surcharge, groundwater, and backfill compaction. The value K in Figure 3 represents either at-rest conditions (K_o) for below grade unyielding walls, or active conditions (K_A) for yielding walls.

6.2.1 Backfill Pressures

6.2.1.1 Yielding Walls

Static Lateral earth pressures and forces from backfill for yielding walls can be expressed as (Refs. 3.2.5 & 3.2.7):

$$\sigma_{Abd} = K_A \gamma_t Z \qquad (Z \le h_1)$$

$$\sigma_{Abw} = K_A\left(\gamma_t Z - \gamma_w (Z - h_1)\right) \qquad (h_1 < Z \le H)$$

$$P_{Ab} = \frac{1}{2}\left(H^2 \gamma_t - h_2^2 \gamma_w\right) K_A$$

where:

σ_{Abd} = Lateral backfill pressure above groundwater table at a depth Z for active case (psf)

σ_{Abw} = Lateral backfill pressure below groundwater table at a depth Z for active case (psf)

P_{Ab} = Total static lateral backfill force for active case (lbs per ft of wall width)

K_A = Coefficient of active lateral earth pressure

γ_t = Total unit weight (pcf)

γ_w = Unit weight of water (62.4 pcf)

Z = Depth below grade (ft) [$Z \leq H$]

H = Total height of wall (ft)

h_1 = Depth of ground water table below grade (ft)

h_2 = Submerged height of wall (ft)

Total static lateral backfill force (P_{Ab}) is acting at a depth of H_{bt} from the surface. H_{bt} is the depth of the centroid of the backfill pressure distribution diagram.

Lateral active earth pressure coefficient is defined as:

$$K_A = \tan^2\left(45 - \frac{\phi'}{2}\right)$$

where:

ϕ' = Effective angle of internal friction

For the case of yielding walls with sloping backfill, the coefficient of active earth pressure is defined by:

$$K_A = \left[\frac{\cos\phi'}{1+\sqrt{\sin\phi'\left(\sin\phi' - \cos\phi' \tan\alpha\right)}}\right]^2$$

where:

α = Backfill slope angle

6.2.1.2 Unyielding Walls

Static Lateral earth pressures and forces from backfill for unyielding walls can be expressed as (Refs. 3.2.5 & 3.2.7):

$$\sigma_{obd} = K_o \gamma_t Z \qquad (Z \leq h_1)$$

$$\sigma_{obw} = K_o\left(\gamma_t Z - \gamma_w (Z - h_1)\right) \qquad (h_1 < Z \leq H)$$

$$P_{ob} = \frac{1}{2}\left(H^2\gamma_t - h_2^2\gamma_w\right)K_o$$

where:

σ_{obd} = Lateral backfill pressure above groundwater table at a depth Z for at-rest case (psf)

σ_{obw} = Lateral backfill pressure below groundwater table at a depth Z for at-rest case (psf)

P_{ob} = Total static lateral backfill force for at-rest case (lbs per ft of wall width)

K_o = Coefficient of at-rest lateral earth pressure

Total static lateral backfill force (P_{ob}) is acting at a depth of H_{bt} from the surface. H_{bt} is the depth of the centroid of the backfill pressure distribution diagram.

For a level backfill surface, lateral at-rest earth pressure coefficient is defined as:

$$K_o = 1 - \sin\phi'$$

6.2.2 Uniform Surcharge Pressures

6.2.2.1 Yielding Walls

Static Lateral earth pressures and forces from uniform vertical surcharge loads at the ground surface for yielding walls can be expressed as:

$$\sigma_{As} = K_A q$$

$$P_{As} = K_A q H$$

where:

σ_{As} = Lateral surcharge pressure for active case [uniform pressure] (psf)

P_{As} = Total lateral surcharge force for active case (lbs per ft of wall width)

q = Uniform surcharge pressure.(psf)

The total lateral surcharge force is acting at a depth of $\frac{H}{2}$ from the surface.

6.2.2.2 Unyielding Walls

Static Lateral earth pressures and forces from uniform vertical surcharge loads at the ground surface for unyielding walls can be expressed as:

$$\sigma_{os} = K_o q$$

$$P_{os} = K_o q H$$

where:

σ_{os} = Lateral surcharge pressure for at-rest case [uniform pressure] (psf)

P_{os} = Total lateral surcharge force for at-rest case (lbs per ft of wall width)

q = Uniform surcharge pressure (psf)

The total lateral surcharge force is acting at a depth of $\frac{H}{2}$ from the surface.

6.2.3 Hydrostatic Pressures

Hydrostatic pressures and forces for both yielding walls and unyielding walls can be expressed as:

$$\sigma_{hz} = \gamma_w (Z - h_1) \qquad (h_1 < Z \le H)$$

$$P_h = \frac{1}{2} h_2^2 \gamma_w$$

where:

σ_{hz} = Lateral hydrostatic pressure at a depth Z (psf)

P_h = Total lateral hydrostatic force (lbs per ft of wall width)

Total lateral hydrostatic force is applied at a depth of $h_1 + \frac{2h_2}{3}$ from the ground surface.

6.2.4 Compaction Pressures

6.2.4.1 Yielding Walls

Horizontal pressures and forces from backfill compaction efforts for yielding walls (active condition, K_A) can be estimated from the following relationships (Ref. 3.2.3):

$$\sigma_{Abc} = \sqrt{\frac{2P\gamma_t}{\pi}} \qquad (Z_{Ac} \le Z \le d_{Ac})$$

$$\sigma_{Ac} = \sqrt{\frac{2P\gamma_t}{\pi}} - (K_A \gamma_t Z) \qquad (Z_{Ac} \le Z \le d_{Ac})$$

$$P_{Ac} = \left(\frac{1 - K_A^2}{K_A}\right)\frac{P}{\pi}$$

$$Z_{Ac} = K_A \sqrt{\frac{2P}{\pi \gamma_t}}$$

$$d_{Ac} = \left(\frac{1}{K_A}\right)\sqrt{\frac{2P}{\pi \gamma_t}}$$

$$P = \frac{Dead\ Weight\ of\ Roller + Centrifugal\ Force}{Roller\ Width}$$

where:

σ_{Abc} = Lateral backfill weight plus compaction pressure at a depth Z for active case (psf)

σ_{Ac} = Lateral compaction pressure at a depth Z for active case (psf)

P_{Ac} = Total lateral compaction force for active case (lbs per ft of wall width)

Z_{Ac} = Depth of maximum lateral compaction pressure for active case (ft)

d_{Ac} = Maximum depth of compaction influence for active case (ft)

P = Roller equivalent weight (lb/ft)

Total lateral compaction force (P_{Ac}) is applied at a depth of H_{ct} from the surface. H_{ct} is the depth of the centroid of the compaction pressure distribution diagram.

6.2.4.2 Unyielding Walls

Horizontal pressures and forces from compaction efforts for unyielding walls (at-rest condition, K_o) can be estimated from the charts provided by Duncan et al. (Refs. 3.2.1 and 3.2.2), as shown on Figures 5 through 7.

The following input parameters are needed to estimate the lateral compaction pressures from the charts:

$$\sigma_{ob} = K_o \gamma_e\ Z$$

$$\bar{q} = P/12$$

$$x, w, t, and\ \phi'$$

where:

σ_{ob} = Lateral at-rest backfill pressure at a depth Z (psf)

γ_e = Effective unit weight [above water table, $\gamma_e = \gamma_t$; below water table $\gamma_e = \gamma_t - \gamma_w$] (pcf)

$\bar{q}$ = Roller equivalent weight in lb/in (Fig. 5) or psi (Figs. 6 and 7)

x = Distance between roller and wall (ft)

w = Width of the roller drum (ft)
t = Compaction layer thickness (ft)
ϕ' = Effective angle of internal friction

In Figures 5 through 7, $\bar{q}$ values are shown by solid lines and σ_{ob} values are shown by dash-dot lines. In order to estimate the lateral backfill weight plus compaction pressures at different depths for the at-rest case (σ_{obc}), the appropriate solid line ($\bar{q}$) in the upper part of the diagram is followed down until it meets the appropriate dash-dot line (σ_{ob}). For a specific $\bar{q}$ value, the maximum depth of compaction influence (d_{oc}) is the depth where the solid line meets the dash-dot line. For conditions other than those listed on the charts, adjustment to σ_{obc} should be made using the multiplier factors given in the tables shown on Figures 5 through 7. Once adjusted σ_{obc} values are estimated, the lateral compaction pressure for the at-rest condition is estimated as:

$$\sigma_{oc} = \sigma_{obc} - \left(K_o \gamma_e Z\right) \qquad\qquad Z \leq d_{oc}$$

where:

σ_{obc} = Lateral backfill weight plus compaction pressure at a depth Z for at-rest case (psf)
σ_{oc} = Lateral compaction pressure at a depth Z for at-rest case (psf)
d_{oc} = Maximum depth of compaction influence for at-rest case (ft)

The total lateral compaction force for at-rest case (P_{oc}), is estimated by integrating the estimated lateral compaction pressures (σ_{oc}) distribution over the maximum depth of compaction influence (d_{oc}).

6.3 Lateral Seismic Loads

Lateral seismic forces are shown in Figure 4 and include contributions from backfill and surcharge pressures. The lateral earth pressure coefficient for the dynamic pressure or force increment (ΔK_E) shown in Figure 4 represents either the at-rest condition coefficient for unyielding walls (ΔK_{oE}) or the active condition coefficient for yielding walls (ΔK_{AE}).

6.3.1 Backfill Loads

6.3.1.1 Yielding Walls

Lateral seismic forces from backfill for yielding walls can be estimated using the Mononabe-Okabe (M-O) method. The lateral forces from backfill, including both static and seismic forces, can be estimated as (Refs. 3.2.4 and 3.2.6):

$$P_{AbE} = \frac{1}{2}\gamma_t H^2 K_{AE}(1-k_v)$$

$$K_{AE} = \frac{\cos^2(\phi' - \psi - \theta)}{\cos\theta\cos^2\psi\cos(\delta+\psi+\theta)\left[1+\sqrt{\frac{\sin(\phi'+\delta)\sin(\phi'-\theta-\alpha)}{\cos(\delta+\psi+\theta)\cos(\alpha-\psi)}}\right]^2}$$

$$\theta = \tan^{-1}\frac{k_h}{1-k_v}$$

$$K_{AE} = \Delta K_{AE} + K_A$$

$$\Delta P_{AE} = \frac{1}{2}(H^2\gamma_t)(K_{AE}-K_A) = \frac{1}{2}(H^2\gamma_t)\Delta K_{AE} \qquad (k_v = 0)$$

$$\sigma_{AE} = \Delta K_{AE}\gamma_t(H-Z) \qquad (k_v = 0)$$

where:

P_{AbE}	=	Total (static plus seismic) backfill lateral force applied to yielding walls (lbs per ft of wall width)
K_{AE}	=	Total (static plus seismic) lateral earth pressure coefficient (g)
ΔK_{AE}	=	Seismic lateral earth pressure coefficient for the dynamic pressure or force increment (g)
ΔP_{AE}	=	Seismic lateral earth force increment applied to yielding walls (lb per ft of wall width)
σ_{AE}	=	Seismic lateral earth pressure increment applied to yielding walls (psf)
ϕ'	=	Effective angle of internal friction
θ	=	Seismic angle
δ	=	Angle of wall friction
α	=	Angle of sloping backfill surface behind wall
ψ	=	Slope of back of wall to vertical
k_h	=	Effective horizontal ground acceleration coefficient (g)
k_v	=	Effective vertical ground acceleration coefficient (g)

Since the horizontal acceleration components for most earthquakes are considerably greater than the vertical acceleration components and the peak values of horizontal and vertical acceleration are not expected to occur simultaneously, the vertical seismic force is often ignored (k_v =0).

For the case of a vertical wall with a <u>horizontal backfill slope</u>, Seed and Whitman (Ref. 3.2.6) showed that, when k_v is zero, the wall is vertical (ψ =0), the wall surface is smooth (δ =0), and

ϕ' is 35° (which may be assumed for most practical cases involving granular fill), a practical and useful approximation for estimating the lateral seismic forces from backfill is:

$$\Delta K_{AE} = K_{AE} - K_A = \frac{3}{4} k_h$$

$$P_{AbE} = \frac{1}{2}\gamma_t H^2 \left(K_A + \frac{3}{4} k_h \right)$$

$$\Delta P_{AE} = \frac{1}{2}\left(H^2 \gamma_t\right)\Delta K_{AE} = \frac{3}{8} H^2 \gamma_t k_h$$

Total seismic lateral earth force increment (ΔP_{AE}) will act at a depth of $0.33H$ below the top of the retained wall height.

For the case of a vertical wall with <u>sloping backfill</u>, when k_v is zero, the wall is vertical (ψ =0), and the wall surface is smooth (δ =0), the lateral seismic forces from sloping backfill using the Mononabe-Okabe formulation is:

$$P_{AbE} = \frac{1}{2}\gamma_t H^2 K_{AE}$$

$$K_{AE} = \frac{\cos^2\left(\phi' - \theta\right)}{\cos^2\theta \left[1 + \sqrt{\frac{\sin\phi' \sin\left(\phi' - \theta - \alpha\right)}{\cos\theta \cos\alpha}} \right]^2}$$

$$\theta = \tan^{-1} k_h$$

$$\Delta P_{AE} = \frac{1}{2}\left(H^2 \gamma_t\right)\left(K_{AE} - K_A\right) = \frac{1}{2}\left(H^2 \gamma_t\right)\Delta K_{AE}$$

For the case of a vertical wall with a submerged horizontal backfill and restrained water condition (low permeability soils with a coefficient of permeability <1 x 10^{-3} cm/sec), the lateral seismic forces from backfill can be estimated using the M-O method and an equivalent seismic angle as:

$$K'_{AE} = \frac{\cos^2\left(\phi' - \psi - \theta'\right)}{\cos\theta' \cos^2\psi \cos\left(\delta + \psi + \theta'\right)\left[1 + \sqrt{\frac{\sin\left(\phi' + \delta\right)\sin\left(\phi' - \theta' - \alpha\right)}{\cos\left(\delta + \psi + \theta'\right)\cos\left(\alpha - \psi\right)}} \right]^2}$$

$$\theta' = \tan^{-1}\left[\frac{\gamma_t}{\gamma_e}\right] k_h \qquad (k_v = 0)$$

$$K'_{AE} = \Delta K'_{AE} + K_A$$

$$\Delta P_{AE} = \frac{1}{2}\left(H^2\gamma_e\right)\left(K'_{AE} - K_A\right) = \frac{1}{2}\left(H^2\gamma_e\right)\Delta K'_{AE} \qquad (k_v = 0)$$

$$\sigma_{AE} = \Delta K'_{AE}\gamma_e\left(H - Z\right) \qquad (k_v = 0)$$

where:

K'_{AE} = Total (static plus seismic) lateral earth pressure coefficient for submerged condition (g)

$\Delta K'_{AE}$ = Seismic lateral earth pressure coefficient for the dynamic pressure or force increment for submerged condition (g)

θ' = Equivalent seismic angle

γ_e = Effective unit weight [above water table, $\gamma_e = \gamma_t$; below water table $\gamma_e = \gamma_t - \gamma_w$] (pcf)

For the case of a vertical wall with a submerged horizontal backfill and free water condition (high-permeability soils), the lateral seismic forces from backfill can be estimated in a manner similar to the restrained water condition, with the exception that the hydrodynamic water forces should be added. The hydrodynamic pressure or force increment can be estimated in a manner similar to the procedure presented in Section 6.3.3.

6.3.1.2 Unyielding Walls

Lateral seismic forces from backfill for unyielding walls can be estimated using the simplified procedure developed by Wood (Refs. 3.2.4 and 3.2.8). The estimated seismic lateral earth force increment is:

$$P_{oE} = \left(H^2\gamma_t\right) f k_h = \frac{1}{2}\gamma_t H^2 \Delta K_{oE}$$

$$\sigma_{oE} = 2 f k_h \gamma_t (H - Z) = \Delta K_{oE}\gamma_t (H - Z)$$

where:

P_{oE} = Seismic lateral force increment applied to unyielding walls (lb per ft of wall width)

σ_{oE} = Seismic lateral pressure increment applied to unyielding walls (psf)

f = Dimensionless thrust factor (see Ref. 3.2.4, Fig. 11.17), but f is approximately equal to unity.

k_h = Horizontal ground acceleration coefficient (g)

The seismic lateral earth force increment (P_{oE}) will act at a depth of $0.33H$ below the top of the retained wall height.

For the case of a vertical wall with a submerged horizontal backfill and restrained water condition (low permeability soils with a coefficient of permeability <1 x 10^{-3} cm/sec), the lateral seismic force or pressure increments from backfill can be estimated using the procedure above and substituting γ_e (effective unit weight) for γ_t (total unit weight) for the submerged portion.

For the case of a vertical wall with a submerged horizontal backfill and free water condition (high-permeability soils), the lateral seismic forces from backfill can be estimated in a manner similar to the restrained water condition with the exception that the hydrodynamic water forces should be added. The hydrodynamic pressure or force increment can be estimated in a manner similar to the procedure presented in Section 6.3.3.

6.3.2 Uniform Surcharge

Lateral seismic forces from uniform vertical surcharge loads for both yielding and unyielding walls can be expressed as:

$$P_{sE} = \Delta K_E q H$$

$$\sigma_{sE} = \Delta K_E q$$

where:

P_{sE} = Lateral seismic surcharge force (lb per ft of wall width)

σ_{sE} = Lateral seismic surcharge pressure (psf)

The lateral seismic surcharge force is acting at a depth of $\frac{H}{2}$ from the ground surface (top of the wall).

6.3.3 Hydrodynamic Pressures

The hydrodynamic pressure, or force increment can be estimated as (Ref. 3.2.4):

$$\sigma_{wd} = \frac{7}{8} k_h \gamma_w \sqrt{h_2 (Z - h_1)} \qquad (h_1 < Z \le H)$$

$$\Delta P_{wd} = \frac{7}{12} k_h \gamma_w Z - h_2^2$$

where:

ΔP_{wd} = Hydrodynamic lateral force increment applied to walls (lb per ft of wall width)

σ_{wd} = Hydrodynamic lateral pressure increment applied to walls (psf)

The hydrodynamic pressure has a parabolic distribution and the force acts at a distance of $0.4h_2$ above the base of the wall.

6.4 Rock Lateral Pressures

For below grade structure walls cast directly against excavated sound rock, the above indicated relationships for unyielding walls are valid and should be followed. However, the lateral at-rest earth pressure coefficient for rock should be estimated as (Ref. 3.2.7):

$$K_o = \frac{\nu}{1-\nu}$$

where:

ν = Poisson's ratio

6.5 Resistance to Lateral Loads

Resistance to lateral loads may be provided by friction along the base of the foundations and by passive pressures acting on the sides of foundations or below grade walls.

6.5.1 Friction Resistance

Ultimate sliding resistance may be estimated by multiplying the dead weight structural loads by a friction coefficient of 0.6 calculated in Ref. 3.1.12 for concrete foundation/limestone or concrete foundation/fill concrete interface. Only buoyant dead weight should be used for that portion of the structure extending below the groundwater level.

The recommended coefficient of sidewall friction at the interface between the sidewall and the backfill soil is 0.35 as calculated in Ref. 3.1.12.

6.5.2 Passive Resistance

The magnitude of passive earth pressures that resist the movement of a structure is controlled by the amount the structure moves and the strength and stiffness of soils or rock that resist its movement. Passive lateral resisting pressures and forces for walls against compacted backfill and sound rock are shown on Figure 8 and discussed below.

6.5.2.1 Walls or Foundations against Compacted Backfill

Passive earth resistance pressures and forces for granular soils backfill can be expressed as (Refs. 3.2.5 & 3.2.7):

$$\sigma_{Pd} = K_P \gamma_t Z = 0 \qquad (0 < Z \le 2)$$

$$\sigma_{Pd} = K_P \gamma_t Z \qquad (2 < Z \le h_1)$$

$$\sigma_{Pw} = K_P \left(\gamma_t Z - \gamma_w (Z - h_1)\right) \qquad (h_1 < Z \le H)$$

$$P_P = \frac{1}{2}\left(H^2 \gamma_t - 4\gamma_t - h_2^2 \gamma_w\right) K_P$$

$$K_P = \tan^2\left(45 + \frac{\phi'}{2}\right)$$

where:

σ_{Pd}	=	Lateral passive resistance pressure above groundwater table (psf)
σ_{Pw}	=	Lateral passive resistance pressure below groundwater table (psf)
P_P	=	Total lateral passive resistance force (lbs per ft of wall width)
K_P	=	Coefficient of passive lateral earth pressure
ϕ'	=	Effective angle of internal friction
γ_t	=	Total unit weight (pcf)
γ_w	=	Unit weight of water (62.4 pcf)
Z	=	Depth below grade (ft) [$Z \le H$]
H	=	Total height of wall (ft)
h_1	=	Depth of ground water table below grade (ft)
h_2	=	Submerged height of wall (ft)

Due to potential post-construction disturbance, excavation or formation of a soil gap near the surface, the passive resistance of the upper 2 feet of soils is neglected. Total lateral passive resistance force (P_P) acts at a depth of H_{bt} from the surface. H_{bt} is the depth of the centroid of the passive pressure distribution diagram.

For compacted granular backfill, a horizontal displacement of about 0.02H at the top of the walls is required in order to mobilize the full passive resisting forces (Ref. 3.2.5). For rigid and unyielding walls, the value of effective angle of internal friction (ϕ') should be limited to a maximum of 15 degrees for calculating the coefficient of passive lateral earth pressure (K_P).

6.5.2.2 Walls or Foundations against Intact Rock

For below grade walls or foundations cast directly against excavated sound rock, the passive resistance forces can be expressed using a similar passive pressure concept as for cohesive soils (Refs. 3.2.5 & 3.2.7):

$$\sigma_{Pd} = \gamma_t Z = 0 \qquad (0 < Z \le 2)$$

$$\sigma_{Pd} = \gamma_t Z + 2C \qquad (2 < Z \le h_1)$$

$$\sigma_{Pw} = \left(\gamma_t Z - \gamma_w (Z - h_1)\right) + 2C \qquad (h_1 < Z \le H)$$

$$P_P = \frac{1}{2}\left(H^2 \gamma_t - h_2^2 \gamma_w\right) + 2CH - (2\gamma_t + 4C)$$

where:

σ_{Pd} = Lateral passive resistance pressure above groundwater table (psf)
σ_{Pw} = Lateral passive resistance pressure below groundwater table (psf)
P_P = Total lateral passive resistance force (lbs per ft of wall width)
C = Unit shear strength at zero normal load along failure plane (psf)
γ_t = Total unit weight (pcf)
γ_w = Unit weight of water (62.4 pcf)
Z = Depth below grade (ft) [$Z \leq H$]
H = Total height of wall (ft)
h_1 = Depth of ground water table below grade (ft)
h_2 = Submerged height of wall (ft)

Due to potential post-construction disturbance, excavation or formation of a soil gap near the surface, the passive resistance of the upper 2 ft of soils is neglected. Total lateral passive resistance force (P_P) acts at a depth of H_{bt} from the surface. H_{bt} is the depth of the centroid of the passive pressure distribution diagram.

Passive pressures below the rock surface can be estimated using the above suggested procedure. However, passive resistance should be limited to 10,000 psf.

7.0 SAMPLE CALCULATIONS

Sample calculations are developed for compacted fill properties provided in Section 5.5.2.2 and the procedures described above.

- Figures 9 and 10 present sample calculations for static lateral active and at-rest pressures, respectively.
- Figures 9a and 10a present lateral total (static and seismic) active and at-rest pressures, respectively.
- Figures 9b and 10b present lateral total (static, seismic, hydrostatic, and hydrodynamic) active and at-rest pressures, respectively.
- Figure 11 presents lateral static passive pressures.

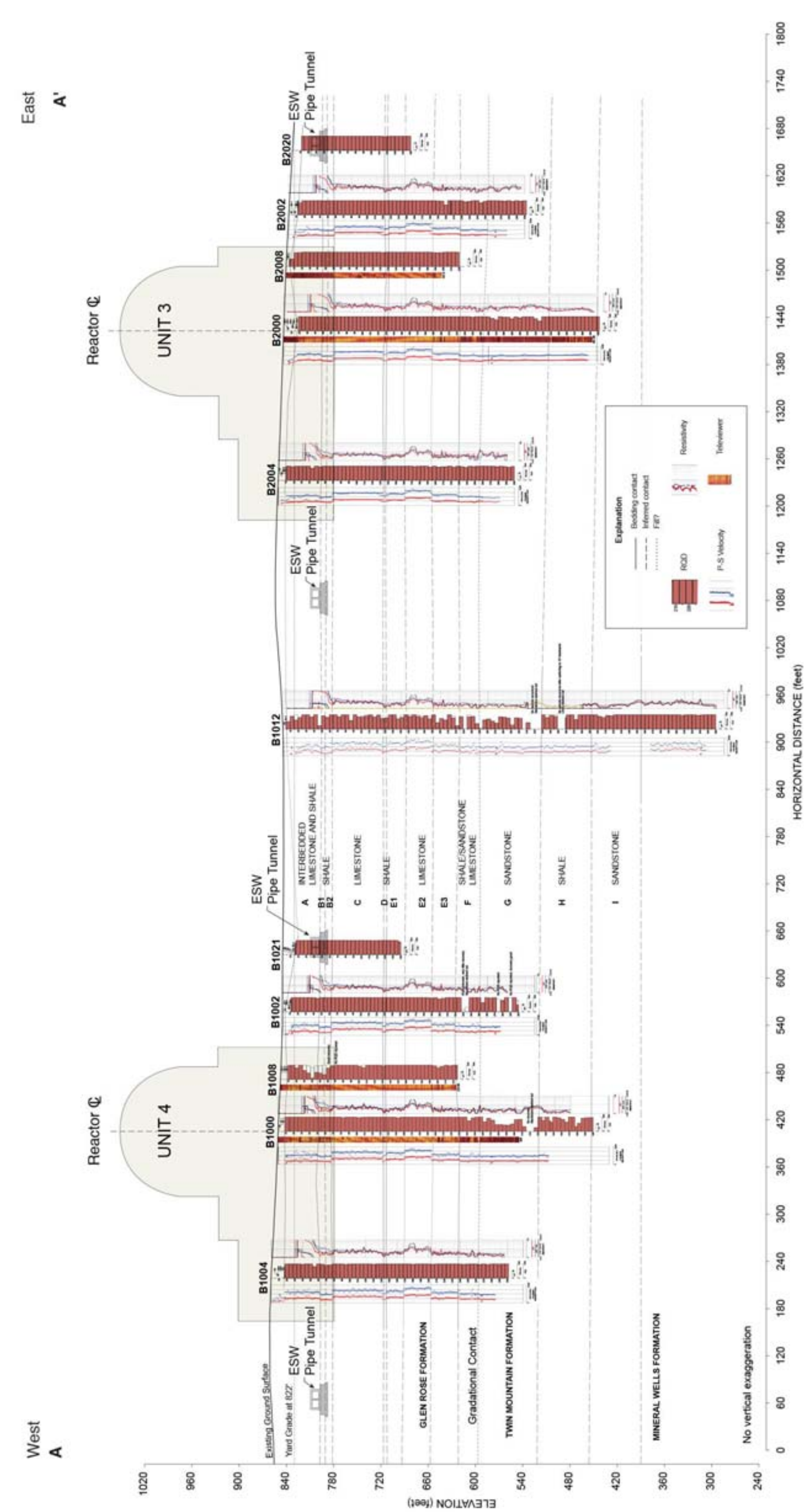
Lateral earth pressures acting on non-yielding walls (rigid and restrained from displacement and rotation), such as the seismic category I and II structures, should be calculated for an at-rest condition. Other walls that are capable of yielding (including flexible or walls that are free to displace or rotate at the top) should be calculated for active conditions.

8.0 SOFTWARE

No computer program was utilized for any of the calculations provided in this document.

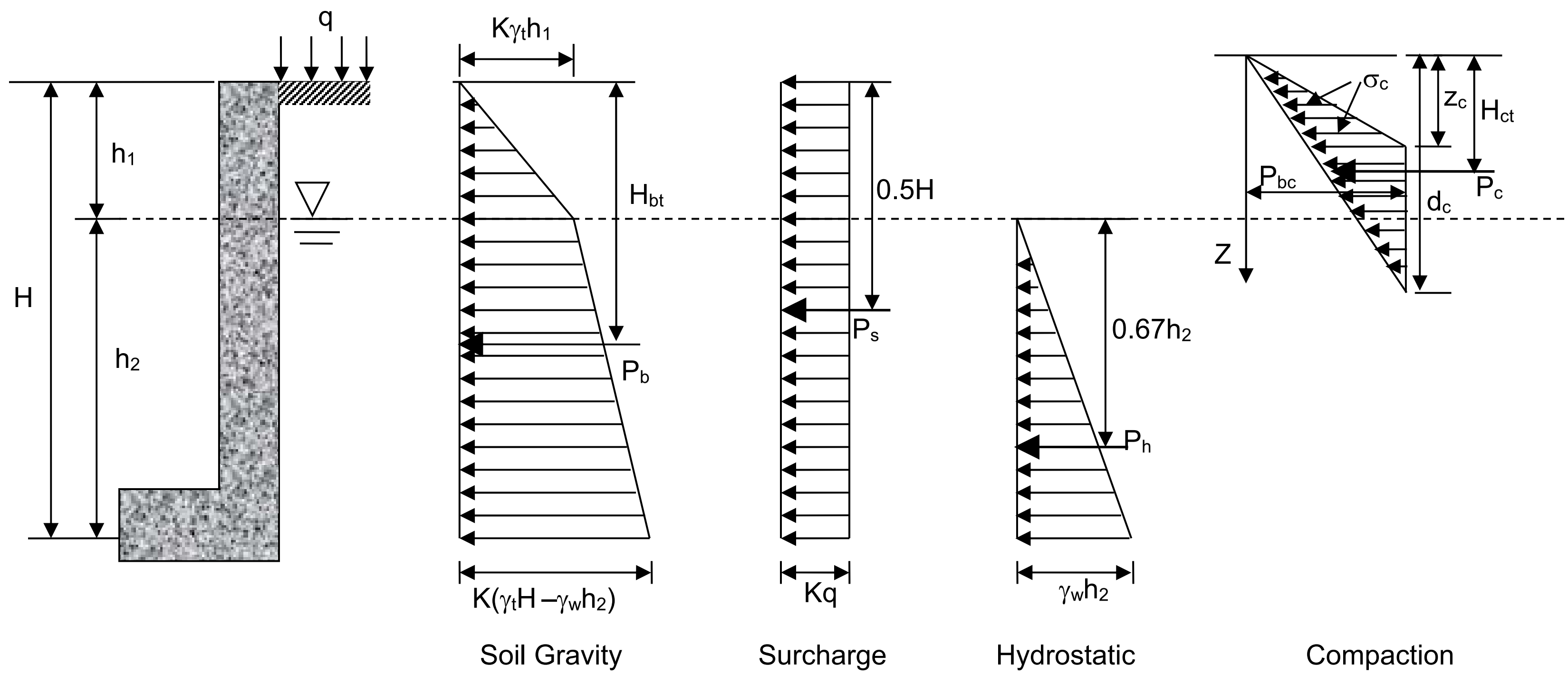
Exploration Locations

FIGURE 1



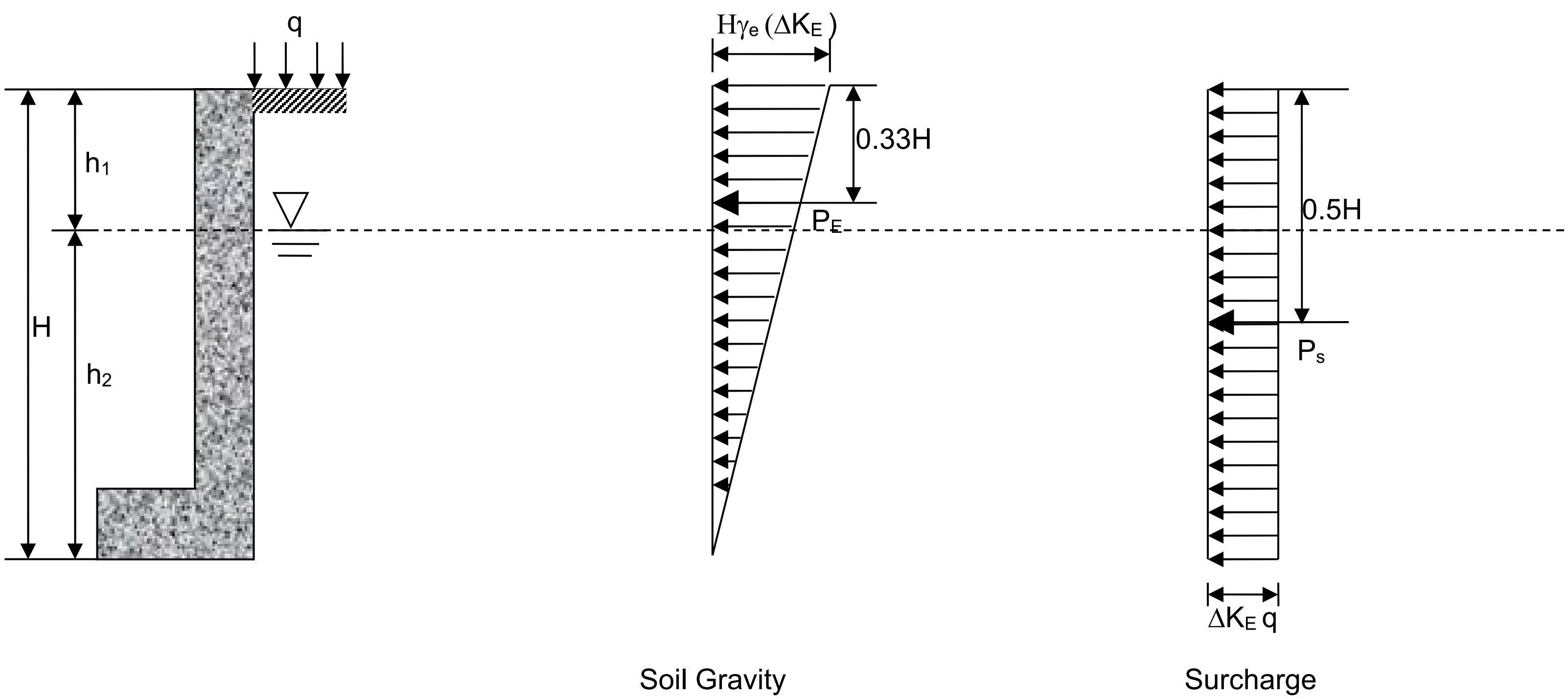
Engineering Cross Section

FIGURE 2



Static Lateral Earth Pressures

FIGURE 3



Seismic Lateral Earth Pressures

FIGURE 4

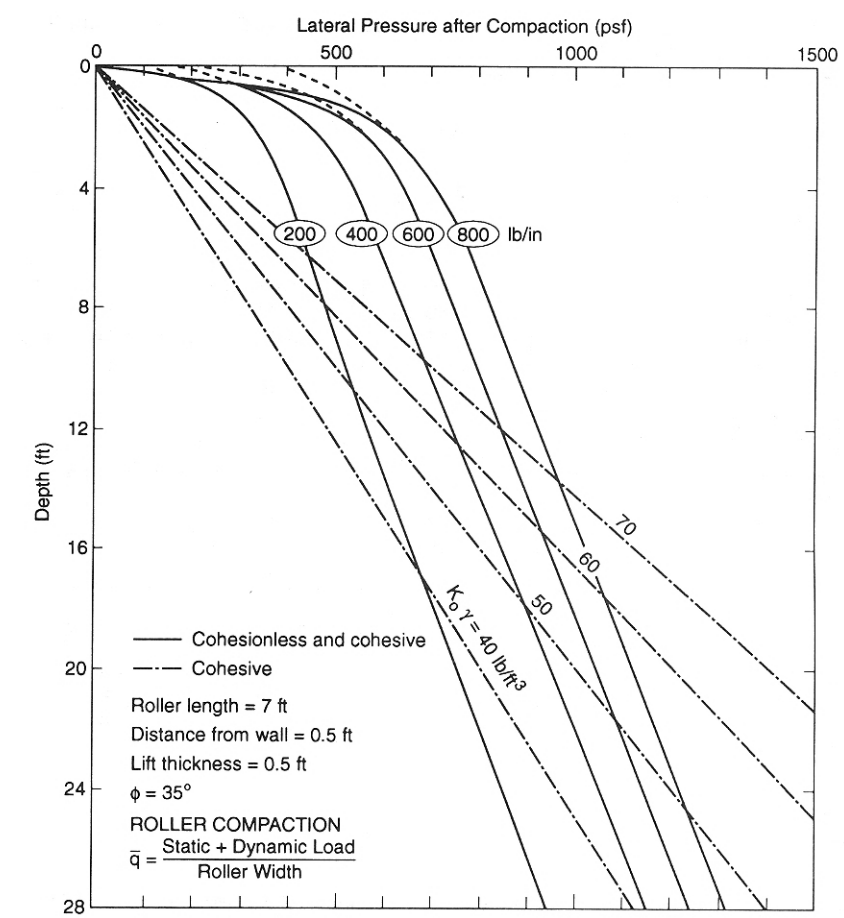


Figure 1: Earth Pressure due to Compaction by Rollers (from Reference 3.2.2)

Variables (1)	Multiplier Factors for z = 2 ft (2)	4 ft (3)	8 ft (4)	16 ft (5)
(*a*) Lift Thickness (t) and Distance from Wall (x) (Adjustment Factors are Combined)				
x = 0.00 ft[a]	1.00	1.00	1.00	1.00
x = 0.20 ft[a]	1.00	1.00	1.00	1.00
x = 0.50 ft[a]	1.00	1.00	1.00	1.00
x = 1.00 ft[a]	0.87	0.88	0.89	0.90
x = 0.00 ft[b]	0.94	0.95	0.95	0.96
x = 0.20 ft[b]	0.94	0.95	0.95	0.96
x = 0.50 ft[b]	0.94	0.95	0.95	0.96
x = 1.00 ft[b]	0.83	0.84	0.86	0.88
(*b*) Roller Width (w)				
w = 1.25 ft	0.80	0.80	0.80	0.88
w = 3.50 ft	0.96	0.94	0.94	0.97
w = 7.00 ft	1.00	1.00	1.00	1.00
w = 10.00 ft	1.00	1.01	1.02	1.04
(*c*) Friction Angle (ϕ)				
ϕ = 25°	0.59	0.70	0.81	0.96
ϕ = 30°	0.75	0.83	0.89	0.98
ϕ = 35°	1.00	1.00	1.00	1.00
ϕ = 40°	1.23	1.16	1.10	1.03

[a] t = 0.5 ft.
[b] t = 1.0 ft.
Note: 1 ft = 0.3048 m.

Table 1: Adjustment Factors for Earth Pressures Induced by Compaction with Rollers (from Reference 3.2.2)

Lateral Compaction Pressures for At-Rest Condition After Duncan et al. (Reference 3.2.2)

FIGURE 5

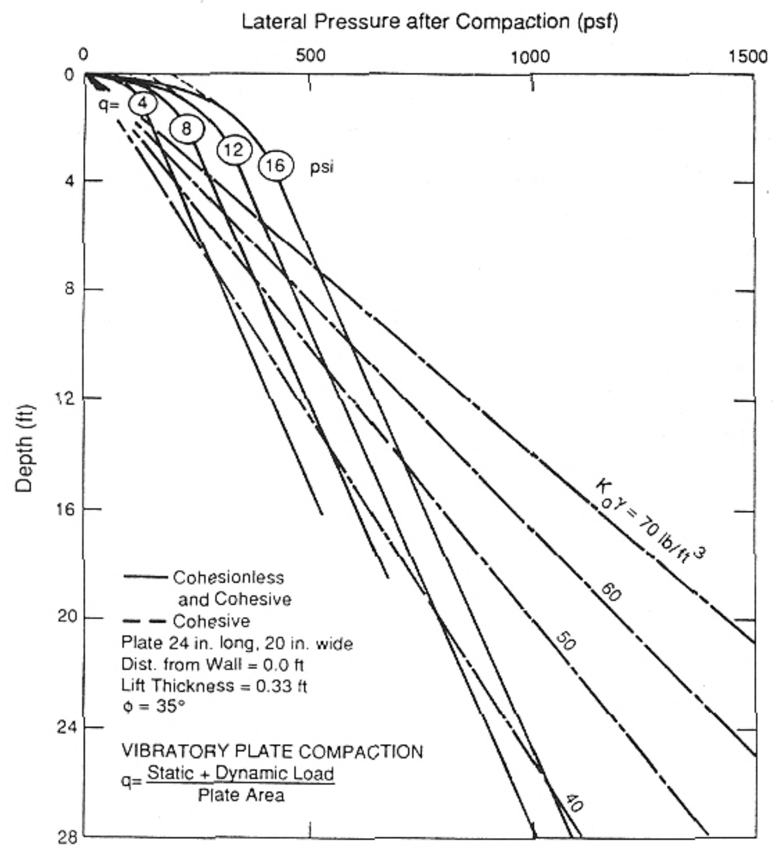


Figure 2: Earth Pressure due to Compaction by Vibratory Plates (from Reference 3.2.1)

Variables (1)	Multiplier Factors for z: 2 ft (2)	4 ft (3)	8 ft (4)	16 ft (5)
(a) Lift thickness (t) and distance from wall (x)				
x = 0.00 ft[a]	1.00	1.00	1.00	1.00
x = 0.50 ft[a]	0.85	0.88	0.88	0.90
x = 0.00 ft[b]	0.87	0.88	0.91	0.95
x = 0.50 ft[b]	0.75	0.75	0.88	0.99
(b) Area of vibratory plate				
Area = 240 sq in.	0.85	0.85	0.90	0.95
Area = 480 sq in.	1.00	1.00	1.00	1.00
Area = 960 sq in.	1.12	1.15	1.11	1.07
(c) Friction angle (ϕ)				
ϕ = 25°	0.70	0.82	0.96	1.00
ϕ = 30°	0.82	0.89	0.98	1.00
ϕ = 35°	1.00	1.00	1.00	1.00
ϕ = 40°	1.15	1.08	1.01	1.00

[a] t = 0.33 ft.
[b] t = 0.50 ft.

Table 2: Adjustment Factors for Earth Pressures Induced by Compaction with Vibratory Plates (from Reference 3.2.1)

Lateral Compaction Pressures for At-Rest Condition After Duncan et al. (Reference 3.2.1)

FIGURE 6

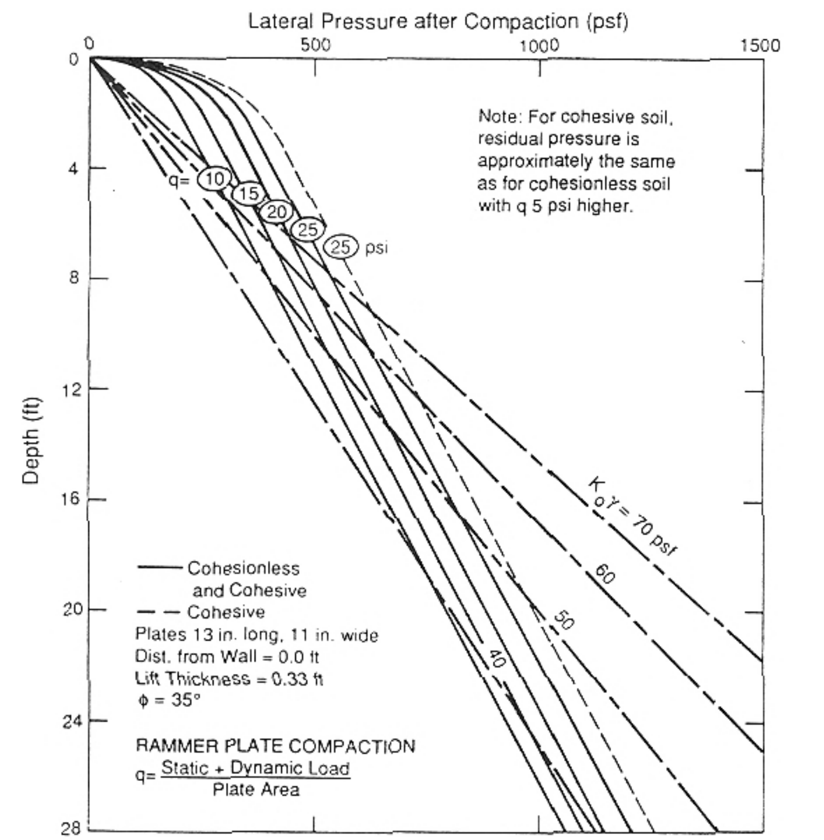


Figure 3: Earth Pressure due to Compaction by Rammer Plates (from Reference 3.2.1)

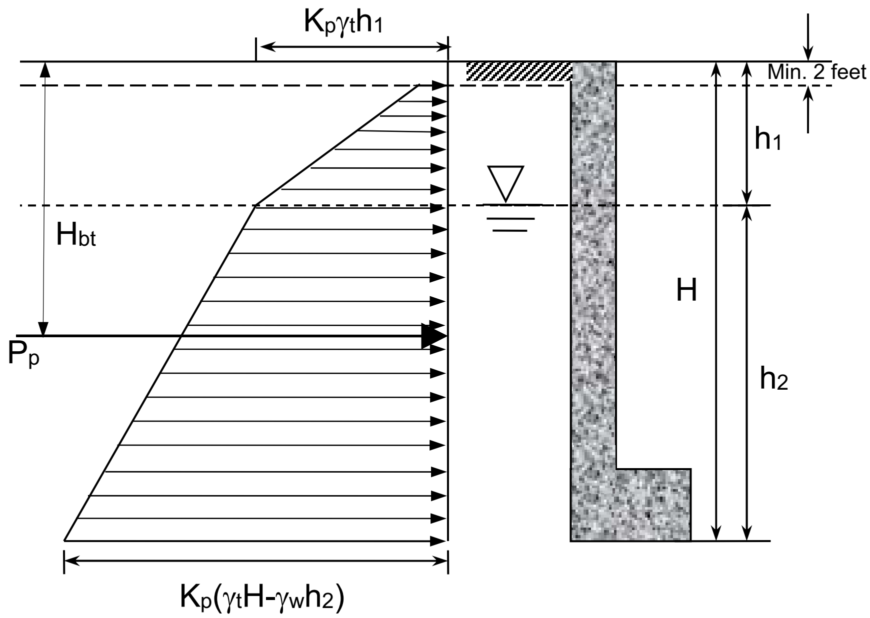
Variables (1)	Multiplier Factors for z: 2 ft (2)	4 ft (3)	8 ft (4)	16 ft (5)
(a) Lift thickness (t) and distance from wall (x)				
x = 0.00 ft[a]	1.00	1.00	1.00	1.00
x = 0.50 ft[a]	0.81	0.82	0.82	0.82
x = 0.00 ft[b]	0.86	0.89	0.93	0.97
x = 0.50 ft[b]	0.72	0.73	0.82	0.90
(b) Area of rammer plate				
Area = 72 sq in.	0.82	0.86	0.92	0.98
Area = 144 sq in.	1.00	1.00	1.00	1.00
Area = 288 sq in.	1.18	1.17	1.10	1.05
(c) Friction angle (ϕ)				
ϕ = 25°	0.68	0.79	0.92	1.00
ϕ = 30°	0.79	0.87	0.95	1.00
ϕ = 35°	1.00	1.00	1.00	1.00
ϕ = 40°	1.18	1.12	1.05	1.00

[a] t = 0.33 ft.
[b] t = 0.50 ft.

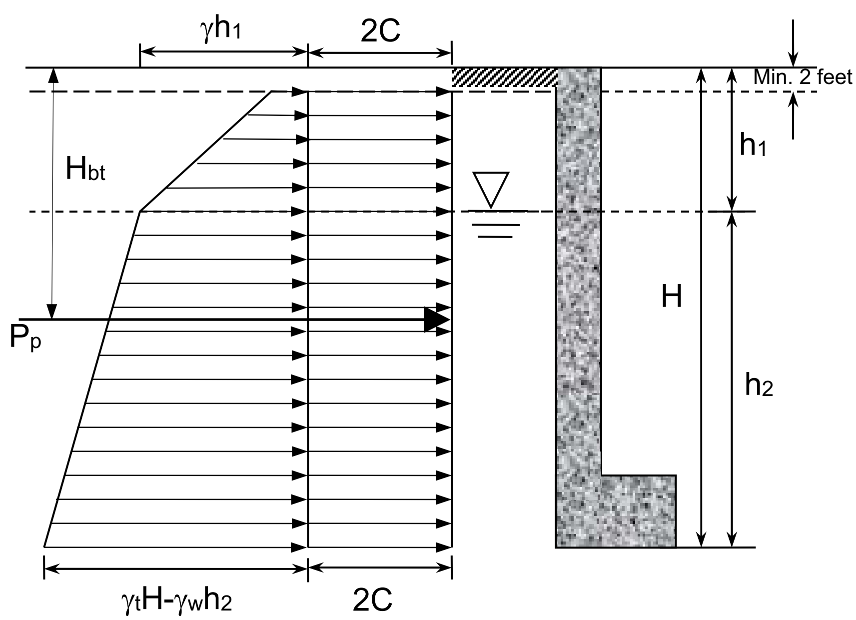
Table 3: Adjustment Factors for Earth Pressures Induced by Compaction with Rammer Plates (from Reference 3.2.1)

Lateral Compaction Pressures for At-Rest Condition
After Duncan et al. (Reference 3.2.1)

FIGURE 7



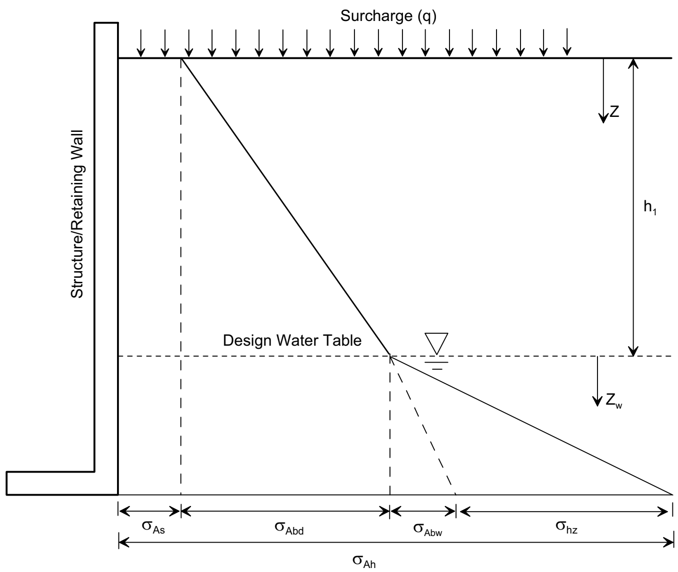
Compacted Fill



Undisturbed Rock

Static Passive Earth Pressures

FIGURE 8



$k_A = \tan^2(45 - \frac{\phi'}{2}) \cong 0.307$ Active earth pressure coefficient

$\sigma_{As} = k_A q \cong 0.307q$ Lateral pressure due to surcharge

$\sigma_{Abd} = k_A \gamma_t Z \cong 38.4Z$ Lateral pressure above water table $(Z \leq h_1)$

$\sigma_{Abw} = k_A(\gamma_t - \gamma_w)Z_w \cong 19.2Z_w$ Lateral pressure increment below h_1 (water table depth)

$\sigma_{hz} = \gamma_w Z_w \cong 62.4Z_w$ Hydrostatic pressure

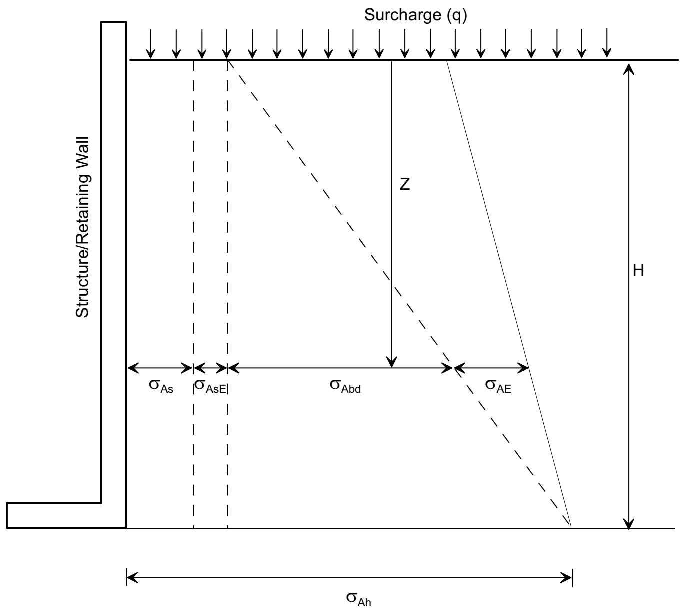
$\sigma_{Ah} = \sigma_{As} + \sigma_{Abd} + \sigma_{Abw} + \sigma_{hz}$ Total active horizontal pressure

Notes:

- Units: lbs/ft^2 for pressure and ft for dimensions.
- Assumed compacted backfill properties:
  - Total unit weight: γ_t =125 lbs/ft^3
  - Internal effective friction angle: ϕ' = 32°
  - Effective cohesion intercept: C′ = 0
- Seismic earth pressure and compaction earth pressure not included.

Active Earth Pressure (Compacted Backfill)

FIGURE 9



$k_A = \tan^2(45 - \frac{\phi'}{2}) \cong 0.307$ Static active earth pressure coefficient

$\Delta K_{AE} = K_{AE} - k_A \cong 0.052$ Seismic active earth pressure coefficient

$\sigma_{As} = k_A q \cong 0.307q$ Static lateral pressure due to surcharge

$\sigma_{Abd} = k_A \gamma_t Z \cong 38.41Z$ Static lateral pressure due to backfill

$\sigma_{AsE} = \Delta K_{AE} q \cong 0.052q$ Seismic lateral pressure due to surcharge

$\sigma_{AE} = \Delta K_{AE} \gamma_t (H - Z) \cong 6.5(H - Z)$ Seismic lateral pressure due to backfill

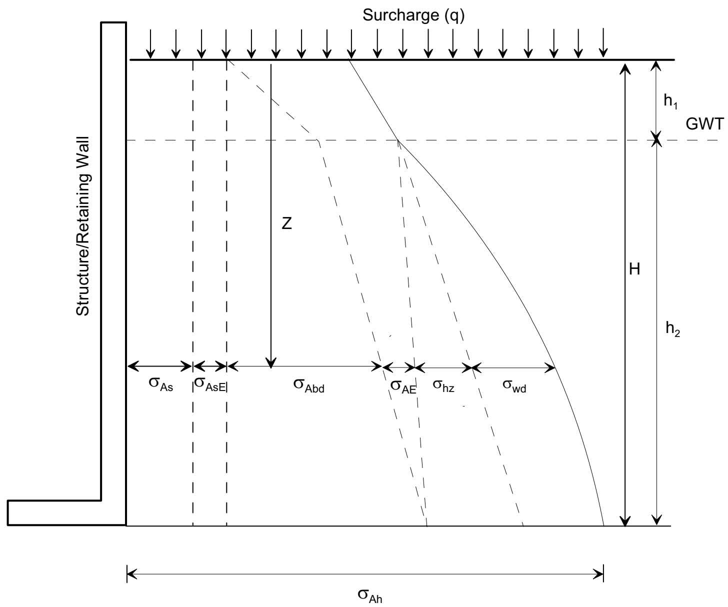
$\sigma_{Ah} = \sigma_{As} + \sigma_{AsE} + \sigma_{Abd} + \sigma_{AE}$ Static plus seismic active horizontal pressure

Notes:

- Units: lbs/ft^2 for pressure and ft for dimensions.
- Assumed compacted backfill properties:
  - Total unit weight: γ_t =125 lbs/ft^3
  - Internal effective friction angle: ϕ' = 32°
  - Effective cohesion intercept: C′ = 0
- Hydrostatic pressure is not included because adequate wall drainage is provided.
- Compaction earth pressure is not included based on the assumption that light compaction equipment is used for compaction of soil adjacent to below-grade walls.

Active Earth Pressure including Seismic Component (Compacted Backfill)

FIGURE 9a



$k_A = \tan^2(45 - \frac{\phi'}{2}) \cong 0.307$ — Static active earth pressure coefficient

$\Delta K'_{AE} = K'_{AE} - k_A \cong 0.133$ — Seismic active earth pressure coefficient (submerged case)

$\sigma_{As} = k_A q \cong 0.307q$ — Static lateral pressure due to surcharge

$\sigma_{AsE} = \Delta K'_{AE} q \cong 0.133q$ — Seismic lateral pressure due to surcharge

$\sigma_{Abd} = k_A \gamma_t Z \cong 38.41Z$ — Static lateral pressure due to backfill above GWT ($Z \leq h_1$)

$\sigma_{Abd} \cong 38.41h_1 + 19.23(Z - h_1)$ — Static lateral pressure due to backfill below GWT ($Z > h_1$)

$\sigma_{AE} = \Delta K'_{AE} \gamma_e (H - Z) \cong 8.33(H - Z)$ — Seismic lateral pressure due to backfill

$\sigma_{hz} = \gamma_w (Z - h_1) \cong 62.4(Z - h_1)$ — Hydrostatic lateral pressure due to GWT ($Z > h_1$)

$\sigma_{wd} = \frac{7}{8} k_h \gamma_w \sqrt{h_2(Z - h_1)} \cong 5.46\sqrt{h_2(Z - h_1)}$ — Hydrodynamic lateral pressure due to GWT ($Z > h_1$)

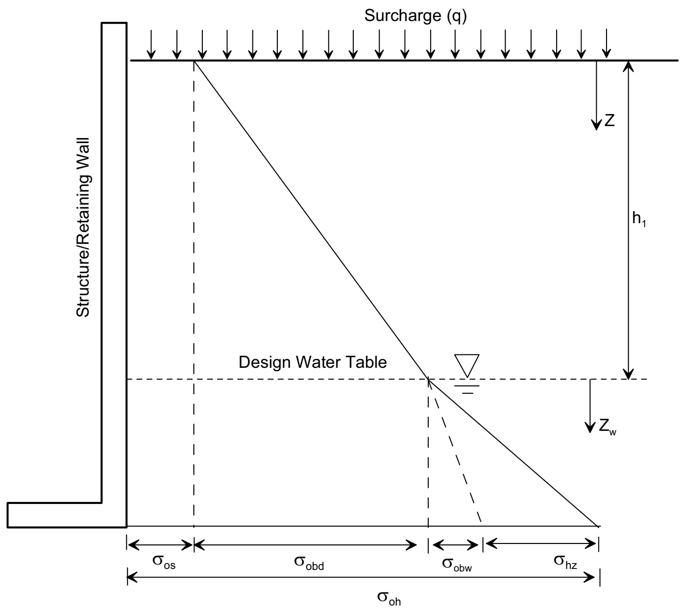
$\sigma_{Ah} = \sigma_{As} + \sigma_{AsE} + \sigma_{Abd} + \sigma_{AE} + \sigma_{hz} + \sigma_{wd}$ — Static plus seismic active horizontal pressure

Notes:

- Units: lbs/ft^2 for pressure and ft for dimensions.
- Assumed compacted backfill properties:
  - Total unit weight: γ_t =125 lbs/ft^3
  - Internal effective friction angle: ϕ' = 32°
  - Effective cohesion intercept: C′ = 0
- Hydrodynamic component does not apply to low permeability soils (k<10^{-3} cm/sec).
- Compaction earth pressure is not included based on the assumption that light compaction equipment is used for compaction of soil adjacent to below-grade walls.

Active Earth Pressure including Hydrostatic & Seismic Components (Compacted Backfill)

FIGURE 9b



$k_o = 1 - \sin\phi' \cong 0.47$ At-rest earth pressure coefficient

$\sigma_{os} = k_o q \cong 0.47q$ Lateral pressure due to surcharge

$\sigma_{obd} = k_o \gamma_t Z \cong 58.8Z$ Lateral pressure above water table $(Z \leq h_1)$

$\sigma_{obw} = k_o(\gamma_t - \gamma_w)Z_w \cong 29.4Z_w$ Lateral pressure increment below h_1 (water table depth)

$\sigma_{hz} = \gamma_w Z_w \cong 62.4Z_w$ Hydrostatic pressure

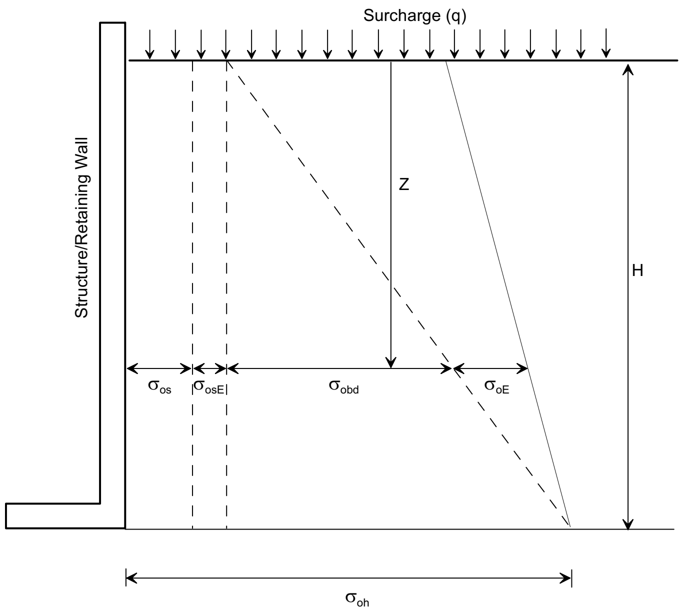
$\sigma_{oh} = \sigma_{os} + \sigma_{obd} + \sigma_{obw} + \sigma_{hz}$ Total at-rest horizontal pressure

Notes:

- Units: lbs/ft^2 for pressure and ft for dimensions.
- Assumed compacted backfill properties:
  - Total unit weight: γ_t =125 lbs/ft^3
  - Internal effective friction angle: ϕ' = 32°
  - Effective cohesion intercept: C′ = 0
- Seismic earth pressure and compaction earth pressure not included.

At-Rest Earth Pressure (Compacted Backfill)

FIGURE 10



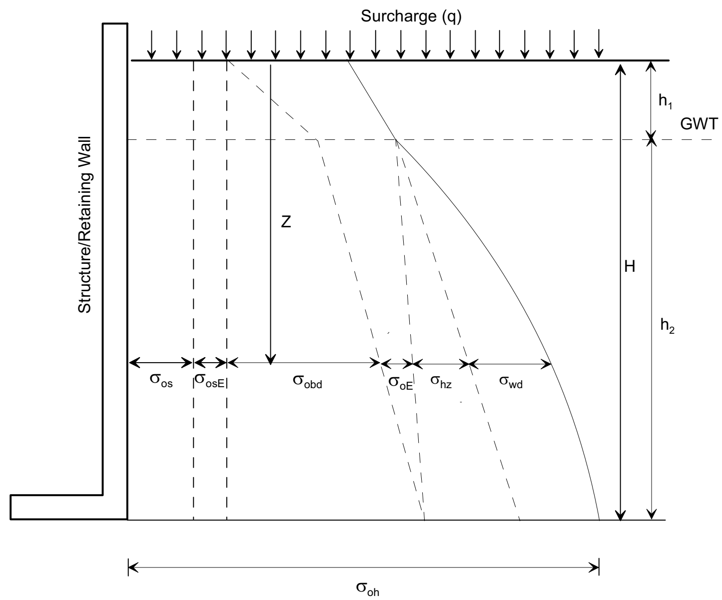
$k_o = 1 - \sin\phi' \cong 0.47$	Static at-rest earth pressure coefficient
$\Delta K_{oE} = 2K_h \cong 0.17$	Seismic at-rest earth pressure coefficient
$\sigma_{os} = k_o q \cong 0.47q$	Static lateral pressure due to surcharge
$\sigma_{obd} = k_o \gamma_t Z \cong 58.8Z$	Static lateral pressure due to backfill
$\sigma_{osE} = \Delta K_{oE} q \cong 0.17q$	Seismic lateral pressure due to surcharge
$\sigma_{oE} = \Delta K_{oE} \gamma_t (H - Z) \cong 21.25(H - Z)$	Seismic lateral pressure due to backfill
$\sigma_{oh} = \sigma_{os} + \sigma_{osE} + \sigma_{obd} + \sigma_{oE}$	Static plus seismic at-rest horizontal pressure

Notes:

- Units: lbs/ft^2 for pressure and ft for dimensions.
- Assumed compacted backfill properties:
  - Total unit weight: γ_t =125 lbs/ft^3
  - Internal effective friction angle: $\phi' = 32°$
  - Effective cohesion intercept: C′ = 0
- Hydrostatic pressure is not included because adequate wall drainage is provided.
- Compaction earth pressure is not included based on the assumption that light compaction equipment is used for compaction of soil adjacent to below-grade walls.

At-Rest Earth Pressure including Seismic Component (Compacted Backfill)

FIGURE 10a



$k_o = 1 - \sin\phi' \cong 0.47$ — Static at-rest earth pressure coefficient

$\Delta K_{oE} = 2K_h \cong 0.20$ — Seismic at-rest earth pressure coefficient

$\sigma_{os} = k_o q \cong 0.47q$ — Static lateral pressure due to surcharge

$\sigma_{osE} = \Delta K_{oE} q \cong 0.2q$ — Seismic lateral pressure due to surcharge

$\sigma_{obd} = k_o \gamma_t Z \cong 58.8Z$ — Static lateral pressure due to backfill above GWT ($Z \leq h_1$)

$\sigma_{obd} \cong 58.8h_1 + 29.43(Z - h_1)$ — Static lateral pressure due to backfill below GWT ($Z > h_1$)

$\sigma_{oE} = \Delta K_{oE} \gamma_e (H - Z) \cong 12.52(H - Z)$ — Seismic lateral pressure due to backfill below GWT ($Z > h_1$)

$\sigma_{oE} \cong 12.52h_2 + 25(h_1 - Z)$ — Seismic lateral pressure due to backfill above GWT ($Z \leq h_1$)

$\sigma_{hz} = \gamma_w (Z - h_1) \cong 62.4(Z - h_1)$ — Hydrostatic lateral pressure due to GWT ($Z > h_1$)

$\sigma_{wd} = \frac{7}{8} k_h \gamma_w \sqrt{h_2(Z - h_1)} \cong 5.46\sqrt{h_2(Z - h_1)}$ — Hydrodynamic lateral pressure due to GWT ($Z > h_1$)

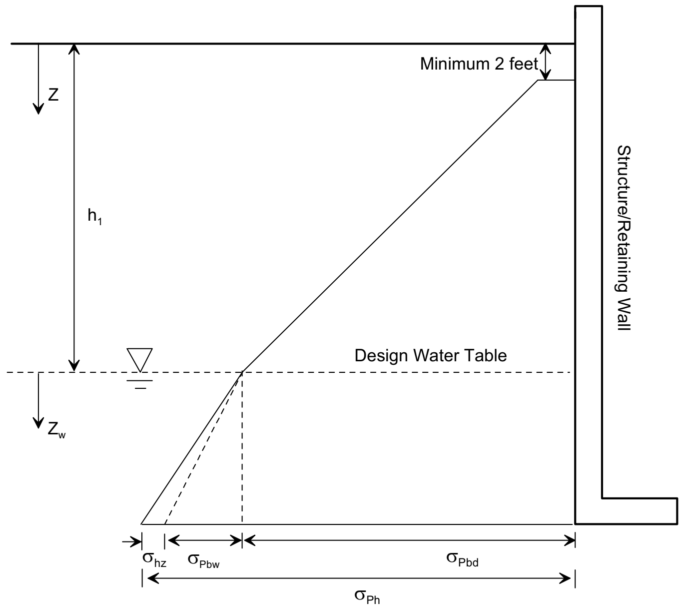
$\sigma_{oh} = \sigma_{os} + \sigma_{osE} + \sigma_{obd} + \sigma_{oE} + \sigma_{hz} + \sigma_{wd}$ — Static plus seismic active horizontal pressure

Notes:

- Units: lbs/ft^2 for pressure and ft for dimensions.
- Assumed compacted backfill properties:
  - Total unit weight: γ_t =125 lbs/ft^3
  - Internal effective friction angle: ϕ' = 32°
  - Effective cohesion intercept: C′ = 0
- Hydrodynamic component does not apply to low permeability soils (k<10^{-3} cm/sec).
- Compaction earth pressure is not included based on the assumption that light compaction equipment is used for compaction of soil adjacent to below-grade walls.

At-Rest Earth Pressure including Hydrostatic & Seismic Components (Compacted Backfill)

FIGURE 10b



$k_P = \tan^2(45 + \frac{\phi'}{2}) = 3.25\ [1.7]$ Passive earth pressure coefficient

$\sigma_{Pbd} = k_P \gamma_t Z \cong 406Z\ [213Z]$ Passive pressure above water table $(2 < Z \le h_1)$

$\sigma_{Pbd} = 0$ No passive pressure for $(Z \le 2)$

$\sigma_{Pbw} = k_P(\gamma_t - \gamma_w)Z_w \cong 203Z_w\ [103\ Z_w]$ Passive pressure increment below h_1 (water table depth)

$\sigma_{hz} = \gamma_w Z_w \cong 62.4Z_w$ Hydrostatic pressure

$\sigma_{Ph} = \sigma_{Ps} + \sigma_{Pbd} + \sigma_{Pbw}$ Total passive (horizontal) pressure

Notes:

- Units: psf for pressure and ft for dimensions.
- Assumed compacted backfill properties:
  - Total unit weight: γ_t=125 pcf
  - Internal effective friction angle: ϕ' = 32°
  - Effective cohesion intercept: C′ = 0
- Seismic earth pressure and compaction earth pressure not included.
- A horizontal displacement of about 0.02H at the top of the walls is required in order to mobilize the full passive resisting forces (H is total wall height). For the case of rigid and unyielding walls, the numbers are shown in brackets (ϕ' is limited to 15°).

Passive Earth Pressure (Compacted Backfill)

FIGURE 11