STRUCTURAL ENGINEERS ASSOCIATION OF SOUTHERN CALIFORNIA

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Presented at PEER-BART/VTA Workshop on
Seismically Induced Earth Pressures, June 8, 2006

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Ground Motion/Site Conditions

White Paper on Seismic Increment of Active Earth Pressure

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INTRODUCTION

Earthquakes can induce earth pressures on retaining walls in addition to those developed by static earth pressures.

Questions arise regarding all types of walls retaining soil related to the method of combining the seismic lateral earth pressure with other building loads, including static lateral earth pressure.

BUILDING CODE REQUIREMENTS

Model code documents (Uniform Building Code, 1997 edition and International Building Code, 2003 edition) have no specific requirements for the seismic increment of active earth pressure to be applied to walls retaining earth.

California Building Code has provisions that deal with the issue of the seismic increment of active earth pressure - The seismic increment of active earth pressure should be applied to buildings with walls that retain earth having exterior grades on opposite sides differing by more than 6 feet

Revised version of Chapter 16, Chapter 16A, which is based on the 1997 UBC for DSA and OSHPD reviewed projects (Section 1630A.1.1 Item 5)

5. Where buildings provide lateral support for walls retaining earth, and the exterior grades on opposite sides of the building differ by more than 6 feet (1829 mm), the load combination of the seismic increment of earth pressure due to earthquake acting on the higher side, as determined by a civil engineer qualified in soils engineering plus the difference in earth pressures shall be added to the lateral forces provided in this section.

CACACACACACA

California Building Code, cont.

Chapter 16A of the 2001 California Building Code, Section 1611.A.6 addresses retaining walls. This section has been modified with amendments to the language in the 1997 UBC as follows:

1611A.6 Retaining Walls. Retaining walls shall be designed to resist loads due to the lateral pressure of retained material in accordance with accepted engineering practice. *Retaining walls higher than 12 feet (3658 mm), as measured from the top of the foundation, shall be designed to resist the additional earth pressure caused by seismic ground shaking.* Walls retaining drained soil, where the surface of the retained soil is level, shall be designed for a load, *H*, equivalent to that exerted by a fluid weighing not less than 30 psf per foot of depth (4.71 kN/m^2/m) and having a depth equal to that of the retained soil. Any surcharge shall be in addition to the equivalent fluid pressure.

Retaining walls shall be designed to resist sliding by at least 1.5 times the lateral force and overturning by at least 1.5 times the overturning moment, using allowable stress design loads.

The resultant of the vertical loads and lateral pressures acting on the wall and its base shall pass through the middle half of the bottom of the footing.

Retaining walls shall be restrained against sliding by friction of the base against the earth, by passive resistance of the soil or by a combination of the two. When used, keys may be assumed to lower the plane of frictional resistance and depth of passive resistance to the level of the bottom of the key. Passive resistance pressures shall be assumed to act on a vertical plane located at the toe of the footing. Overturning shall be computed about the bottom of the spread footing. Passive resistance on the face of the wall may be included in computing resistance to overturning. Frictional resistance on the face of the wall may be included in computing resistance to overturning, except when lateral loads include seismic forces. See Section 1611A.13 for overturning provisions for free-standing walls.

Gravity-type retaining walls utilizing precast concrete units may be used as an alternative to the conventional cantilever retaining systems only after they have been accepted by the enforcement agency.

COMMENTS ON THE CALIFORNIA BUILDING CODE REQUIREMENTS

The CBC requirements in Chapter 16A, Section 1630A, (6-foot criteria) are to determine, in part, the minimum design lateral forces on the structure. These provisions explicitly state that "…the load combination of the seismic increment of earth pressure due to earthquake acting on the higher side… plus the difference in earth pressures shall be added to the lateral forces…" Thus the intent of the code language is to ensure that the seismic earth pressures are included on the higher side of the subterranean walls where there is a difference of 6 feet or greater in exterior grades on the opposite sides.

The CBC requirements given in Section 1611A.6 (12-foot criteria) are for "retaining walls." The context of the section clearly identifies the intent of the section to apply to free-standing cantilever or similar unrestrained walls, and are not intended for subterranean walls of buildings.

NEHRP AND FUTURE BUILDING CODE PROVISIONS

"NEHRP Recommended Provisions for Seismic Regulations for New Buildings and Other Structures," 2000 Edition (Part 1 – Provisions, also known as the FEMA 368 report) does not contain any explicit recommended provisions for accounting of seismic earth pressures for design of retaining walls in the recommended provisions.

FEMA 369

FEMA 369 report (Part 2 – Commentary) contains almost five pages of commentary on the consideration of lateral pressures on earth retaining structures. Section 7.5.1 of the commentary states that "In addition to the potential site hazard discussed in *Provisions* Sec. 7.4.1, consideration of lateral pressures on earth retaining structures shall be included in investigations for Seismic Design Categories D, E, and F."

FEMA 369 cont.

The FEMA 369 commentary states that "…increased lateral pressures on retaining structures during earthquakes have long been recognized; however, design procedures have not been prescribed in U.S. model building codes."

FEMA 369 cont.

Waterfront structures have often performed poorly in major earthquakes due to excess pore water pressure and liquefaction conditions developing in relatively loose, saturated granular soils.

FEMA 369 cont.

Damage reports for structures away from waterfronts are generally limited with only a few cases of stability failures or large permanent movements.

FEMA 369 cont.

- Two categories of walls:
  - "yielding" walls – walls that can move sufficiently to develop minimum active earth pressures
  - "nonyielding" walls – walls that do not satisfy the movement condition

FEMA 369 cont.

- For yielding walls, the FEMA 369 commentary states that there is consensus in the geotechnical engineering practice that a simplified Mononobe-Okabe seismic coefficient analysis reasonably represents the dynamic (seismic) lateral earth pressure increment for yielding retaining walls. The commentary presents an equation for evaluation of the dynamic incremental component (*DPAE*) proposed by Seed and Whitman (1970):

$$\Delta P_{AE} \sim (3/8) k_h \gamma H^2$$

- where k_h is the "horizontal ground acceleration divided by gravitational acceleration."

FEMA 369 cont.

- For nonyielding walls, the FEMA 369 commentary presents an equation developed by Wood (1973) for a rigid nonyielding wall retaining a homogeneous linear elastic soil and connected to a rigid base. The dynamic thrust, *DPE*, is approximately:

$$\Delta P_E = k_h \gamma H^2$$

- As for yielding walls, the point of application of the dynamic thrust is typically taken at a height of 0.6*H* above the base of the wall.

FEMA 369 cont.

- the dynamic earth pressures on nonyielding walls were more consistent with the Mononobe-Okabe solution and that the dynamic wall pressures were strongly correlated with the rocking response of the structure, except for structures founded on rock or hard soil where there is no significant rocking. The commentary suggests that dynamic earth pressure solutions would range from the Mononobe-Okabe solution as a “lower” bound to the Wood solution as an “upper” bound.

COMMENTS ON THE NEHRP COMMENTARY REGARDING SEISMIC DESIGN OF RETAINING WALLS

- The commentary does not provide recommendations on the height of the retained earth such as given in the California Building Code.
- The seismic coefficient should not be equal to the peak ground acceleration - the value should be significantly lower, generally below 0.15.
  - The reason for the reduced value of seismic coefficient compared to the peak ground acceleration is well documented and is due to two factors:
    - a reduction based upon the use of an effective ground acceleration rather than a peak ground acceleration (to take into effect the “repeatable” ground motion), and
    - a reduction to account for the averaging of the lateral forces on the retaining wall over the height of the wall.
  - k_h should be taken as one-third to two-thirds of the peak ground acceleration. In the absence of more detailed analyses, a k_h equal to one-half of the peak ground acceleration may be considered reasonable.

SEI/ASCE 7-02 STANDARD REQUIREMENTS

The ASCE "Minimum Design Loads for Buildings and Other Structures" contains provisions referenced in the International Building Code. Section 9 of the standard, entitled "Earthquake Loads", is based on the 2000 NEHRP Recommended Provisions for Seismic Regulations for New Buildings. The only provision for accounting of seismic earth pressures for design of retaining walls is provided in Section 9.7.5.1 of the Standard, as presented below:

9.7.5.1 Investigation. The owner shall submit to the authority having jurisdiction a written report that includes an evaluation of the items in Section 9.7.4.1 and the determination of lateral pressures on basement and retaining walls due to earthquake motions.

COMMENTS ON ASCE 7-02

Section 9.7.5.1 applies to both basement and cantilever walls. Section 9.7.5.1 is similar to the NEHRP 2000 Commentary, Section 7.5.1. However, ASCE 7-02 does not provide any discussions on how the lateral earth pressures due to earthquake motions are to be estimated.

DAMAGE TO SUBTERRANEAN WALLS IN EARTHQUAKES

- To the authors' knowledge, no reports of any damage to building basement walls retaining earth have been made for the 1971 San Fernando, 1987 Whittier Narrows, 1989 Loma Prieta, and 1994 Northridge earthquakes. There is documented damage to retaining walls during earthquakes, however, the large majority of the reports relate to cantilevered retaining walls or walls at waterfronts. There are no reports of failures in subterranean building walls retaining earth.

ISSUES REGARDING SEISMIC EARTH PRESSURE ON EARTH RETAINING WALLS

Presented at PEER-BART/VTA Workshop on
Seismically Induced Earth Pressures, June 8, 2006

ISSUE: DO SEISMIC EARTH PRESSURES NEED TO BE APPLIED ON SUBTERRANEAN BUILDING WALLS?

- Shear waves propagate vertically.
- The footprint of most buildings is relatively small.
- Building structure and surrounding soil in a like manner and both should be in phase together.
- Depth of embedment of buildings is generally limited to 50 or 60 feet typically or up to 100 feet at most

ISSUE: DO SEISMIC EARTH PRESSURES NEED TO BE APPLIED ON SUBTERRANEAN BUILDING WALLS?

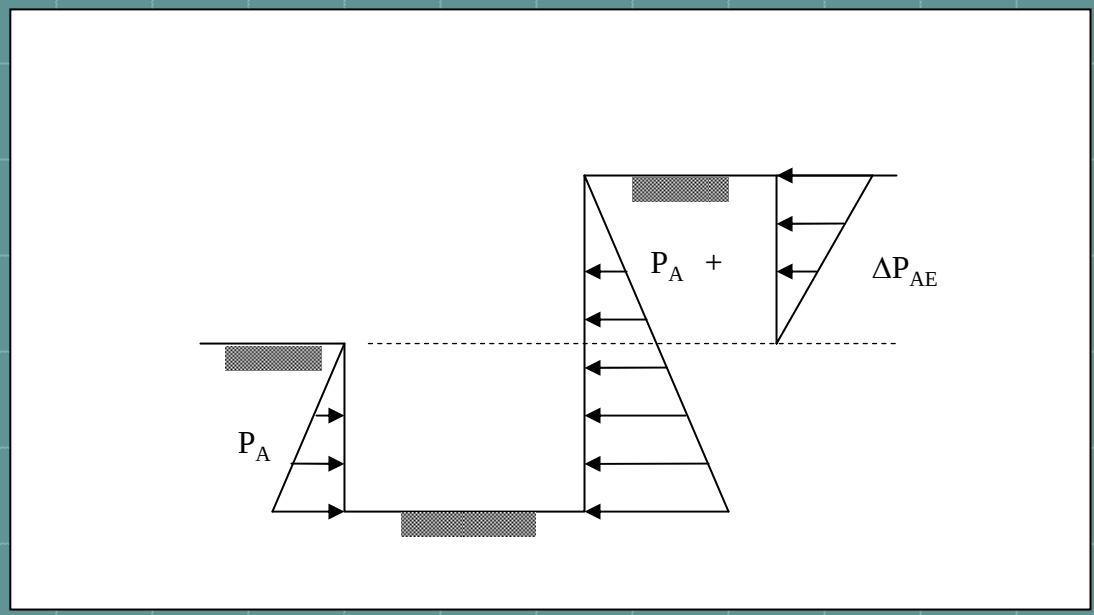
- Therefore, the motions in the ground would be expected to be nearly the same from the bottom of the embedded structure to the ground surface.
- The embedded structure and the surrounding soil will move together - when the subterranean portions of the building are surrounded by soil on all sides at the same elevation
- Therefore, it is the recommendation that the seismic increment of lateral earth pressure not be included for basement walls, unless:
  - The basement may acts out of phase with the surrounding soil or
  - if the structure is very large in plan view

ISSUE: SHOULD PRESSURES ONLY BE APPLIED WHEN THERE IS DIFFERENCE IN THE LEVEL OF THE EARTH RETAINED ON OPPOSITE SIDES OF THE BUILDING?

- It is recommended that a seismic increment of lateral earth pressure be applied when there is a difference in grade across a basement.

ISSUE: SHOULD THE SEISMIC INCREMENT BE APPLIED OVER THE FULL HEIGHT OF THE

It is appropriate that seismic earth pressures should be applied to the unbalanced height of retained earth

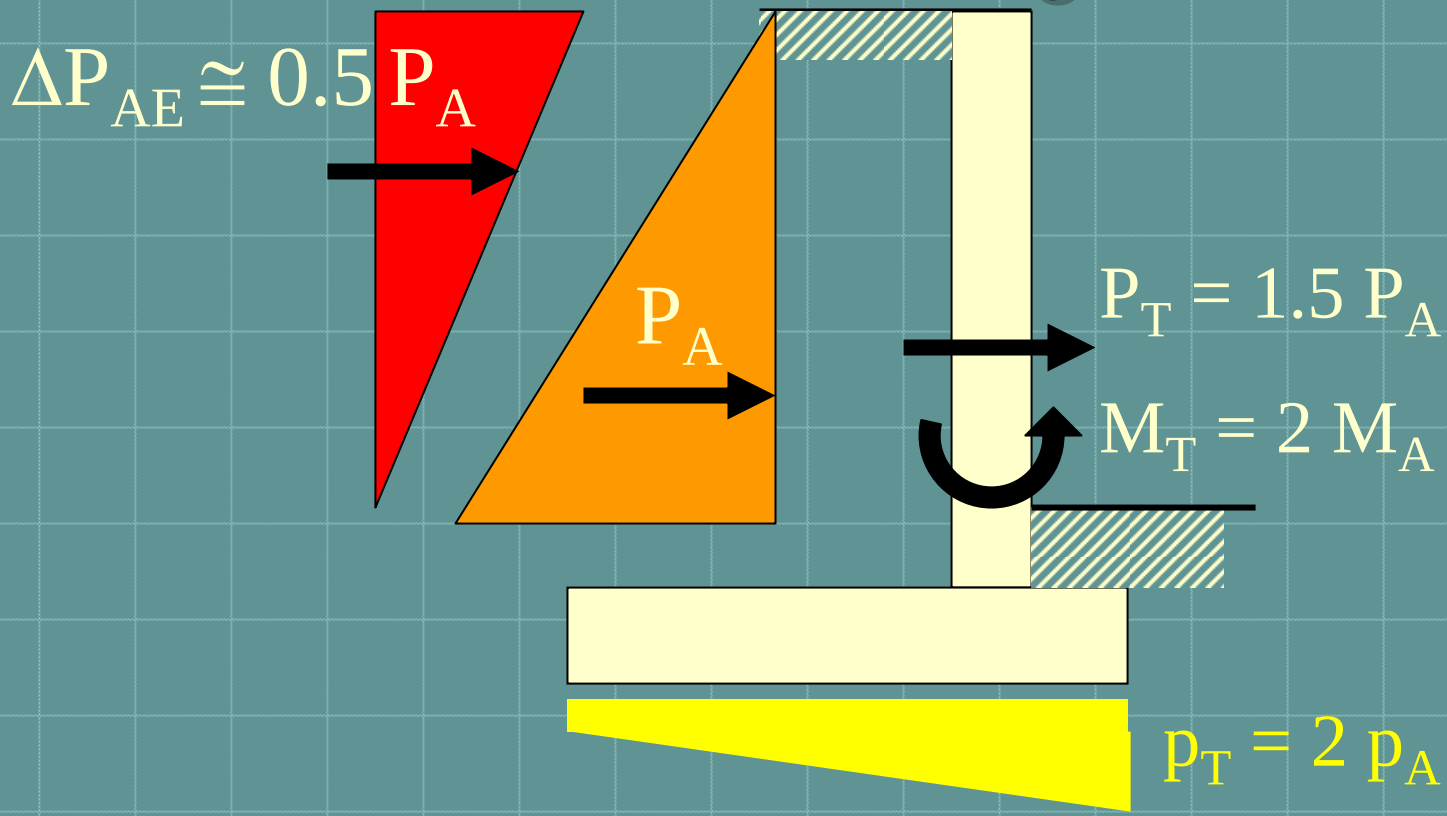


Issue: Load Factor and Reduction of the Seismic Increment

- The seismic increment of earth pressure is derived from the "unreduced" Design Basis Earthquake
- Recommend using a Load Factor of 1.0 for cantilevered retaining walls, which is conservative
- Recommend using a reduction factor "R*" when designing lateral-load resisting elements below grade

Issue: Load Factor of the Seismic Increment

Cantilevered Retaining Walls



Issue: Load Factor of the Seismic Increment Cantilevered Retaining Walls

Total Force "Demand" =	1.5 P_A	If seismic forces not considered:
Total Moment "Demand" =	2.0 M_A	
Total "Factored" Design Force (Capacity): $P_{TU} = (1.7 \times 1.0\ P_A) + (1.0 \times 0.5\ P_A)$ =	2.2 P_A	1.7 P_A
Total "Factored" Design Moment: (Capacity) =	2.7 M_A	1.7 M_A
Total Force "Demand/Capacity" =	0.68	0.88
Total Moment "Demand/Capacity" =	0.74	1.18
Factors not considered: Overstrength, RF, Overestimate of P_A , Sliding Block, …		

Issue: Load Factor of the Seismic Increment

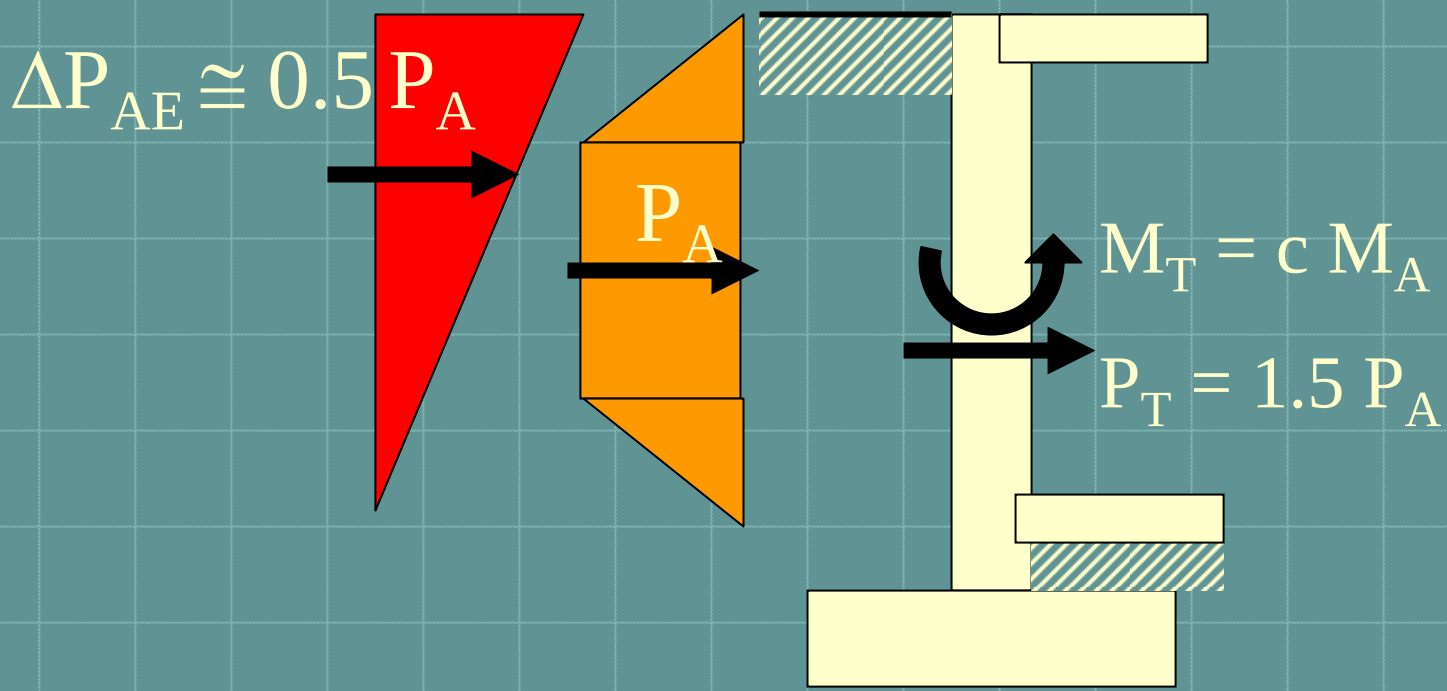
Cantilevered Retaining Walls

Foundation Design:		If seismic forces not considered
Total Soil Pressure "Demand" =	2.0 p_A	
Soil Pressure "Design" Load =	2.0 p_A	1.0 p_A
Ultimate Soil Pressure FS for "Short-duration Load" or for "Active Load"	2.0	2.5
Soil Pressure Ultimate "Capacity"	4.0 p_A	2.5 p_A
Total Soil Pressure "Demand/Capacity" =	2/4 =0.50	2/2.5=0.80

Factors not considered: Overestimate of P_A , Sliding Block, ...

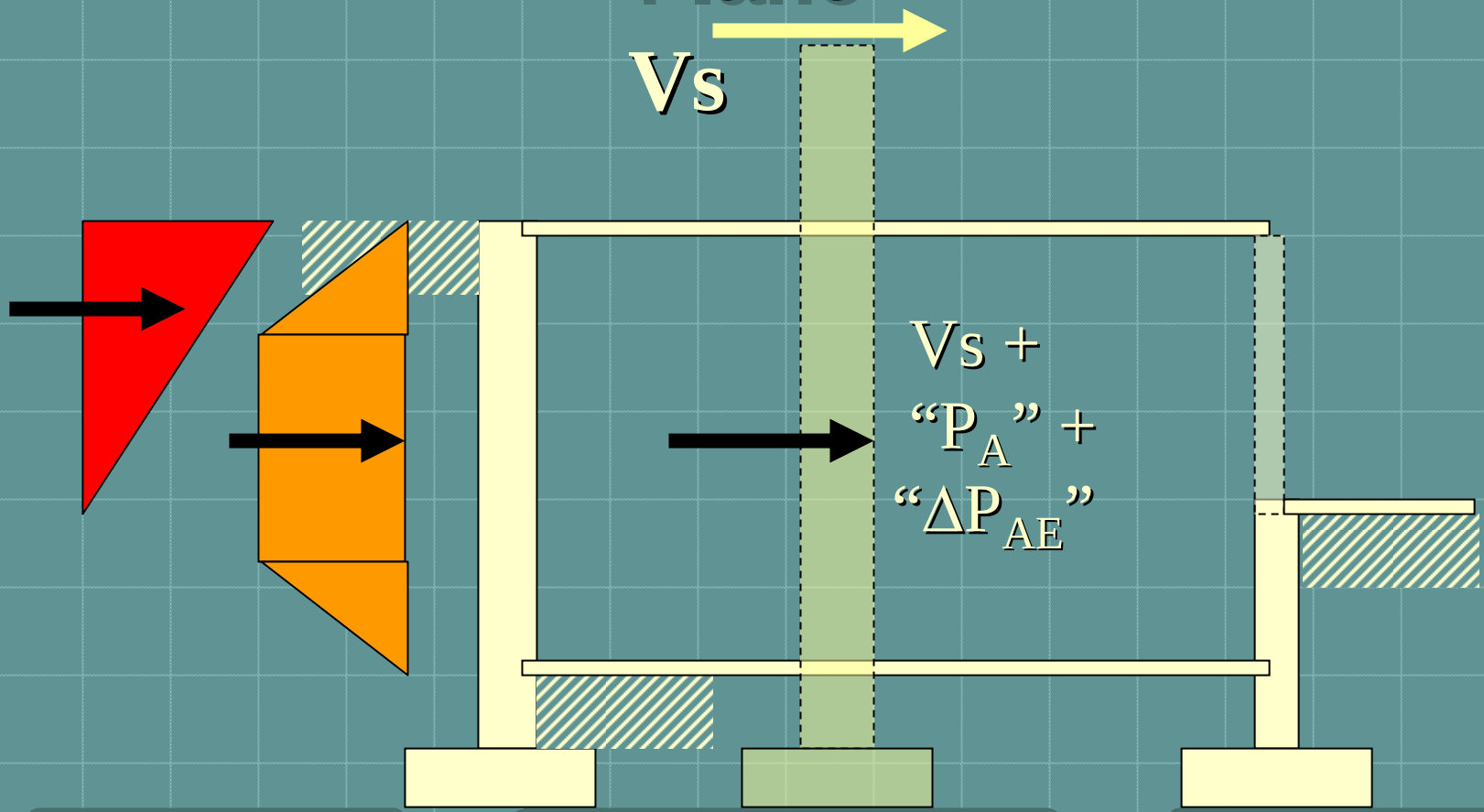
Issue: Load Factor for Seismic Increment

Basement Retaining Walls – "Out-of-Plane"



Issue: Load Factor and Reduction

Lateral-load Resisting Elements "in-Plane"



Issue: Load Factor and Reduction

Lateral-load Resisting Elements "in-Plane"

- Superstructure seismic "strength design" base shear (Vs) is reduced by a factor "R"
- "Active" soil pressure is multiplied by 1.7 when added to Vs
- The Load Factor for the seismic increment of earth pressure need not be more than 1.0
- Seismic increment of soil pressure maybe also reduced by an "R*" for consistency with Vs (overstrength and inelastic/ductility of lateral-load resisting elements)
- A small "R*" may be recommended.

ISSUE: HOW DO WE RECONCILE DESIGNING WALLS FOR SEISMIC EARTH PRESSURES THAT ARE STRONGER AND LARGER WHEN WALLS DESIGNED WITHOUT CONSIDERATION OF SEISMIC EARTH PRESSURES HAVE NOT SHOWN ANY EVIDENCE OF DISTRESS IN RECENT EARTHQUAKES?

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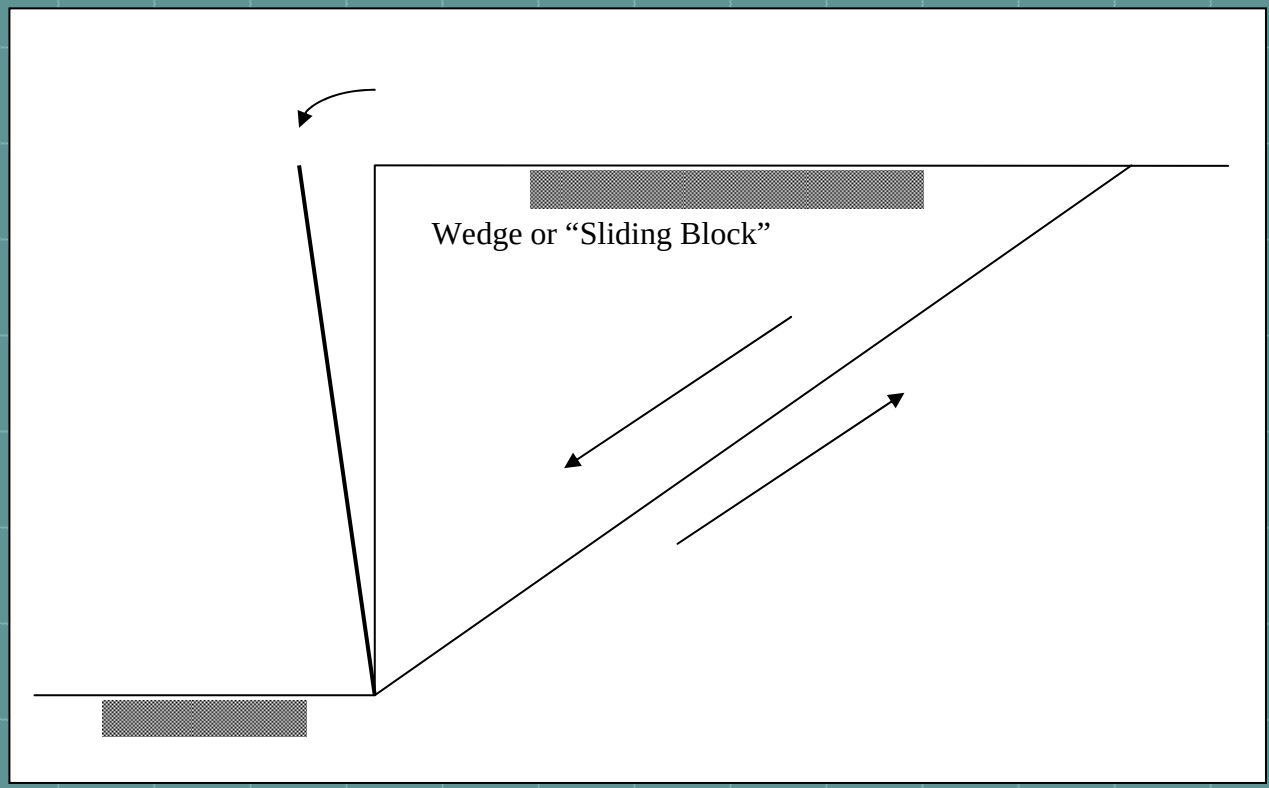
Consider Deformations of Wall



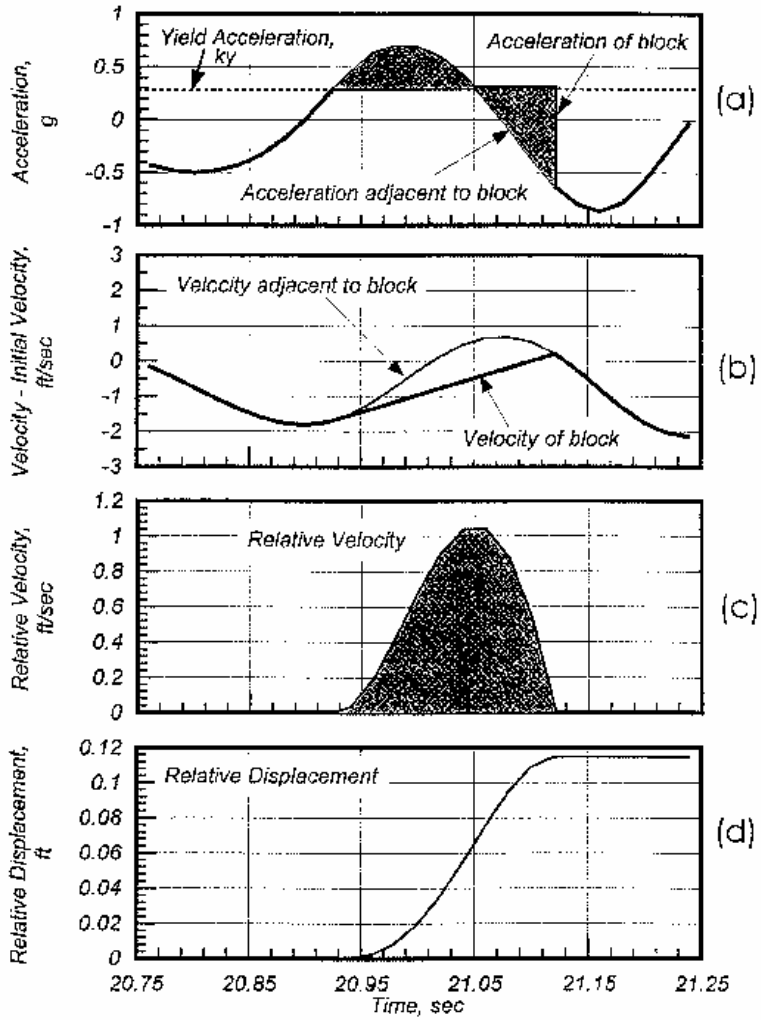


Figure 7
Seismic Coefficient Calculation Procedure

CONCLUSION

- At the present time, it appears appropriate to use judgment in recommendations of seismic lateral earth pressures, especially for basement walls. For free-standing retaining walls, established methods can be employed to estimate the seismic lateral earth pressures, but the results should also be tempered in light of the response of actual retaining walls.