ON THE BEHAVIOR OF
RIGIDLY FRAMED EARTH
RETAINING STRUCTURES
AN EXPERIMENTAL & NUMERICAL STUDY

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Presented in Partial Fulfillment of the Requirements for the Degree of Doctor of Philosophy
The problem

- Encountered several times in the course of my professional practice in and outside the U.S.
- The severe distress of structures with rigid frames as their main lateral force resisting system, retaining earth on one side, and subject to large temperature changes.
- Distress exhibited through unacceptably large deformation of the structure accompanied by structural failure or near failure of structural members.
An Example
A Case Study

- A four Story reinforced concrete parking garage
A Case Study

Section A-A
A Case Study
A Case Study

- Typical Framing Plan
The Case Study

- What Happened?
  - Is it that the structure is inadequately designed to resist the lateral earth pressure?
  - Are the properties of the constructed structure not as specified?
  - Is the backfill soil exerting larger than the established range of pressures often encountered in soil masses?
  - Was it an earthquake?

- To find out more, a 3-D numerical back-analysis was performed on the structure
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- Analysis model all included all structural elements and restraints.
- The earth pressure was applied as a simplified “hydrostatic” force on the building wall.

- The lateral earth pressure magnitude determined from the classical solutions did not adequately predict the building deformation.
- Back analysis indicated a pressure magnitude over 6 times larger than classical solutions.
Preliminary Inference

- Engineering analysis methods may be inadequate to explain the behavior of the structure.
- For safety purposes, monitoring the structure while stabilizing solutions were devised was necessary.
Presentation Content

- Introduction
- Literature Review
- Instrumentation of Full Scale Structure

- Monitoring of Full Scale Structure
- Numerical Analysis of Full Scale Structure
- Parametric Numerical Analysis – Earth Pressure at Backfill

- Par. Num. Analysis of Single Story RFERS
- Par. Num. Analysis of Multi Story RFERS
- Conclusions and Recommendations

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Unfavorable land features coupled with financial constraints often limit the options for real estate improvements.

- Hillside structures
- Buildings with accessory structures and limited space
Behavior, Analysis and Design of rigid frames is well documented

Behavior of earth backfill behind common retaining structures is well understood

Behavior of **rigid frames retaining earth backfill** received no attention in the literature

Of Particular Interest: (1) Magnitude and distribution of lateral earth pressure at backfill, and (2) Temperature changes and soil-structure interaction
Introduction (Cont.)

- Magnitude and distribution of the lateral earth pressure at backfill
  - Nearly all lateral earth pressure theories have been developed for wall like structures (flexible, rigid, braced, or anchored)
  - Classical lateral earth pressure solutions may not be adequate for engineering analysis of RFERS
  - National Building Codes provisions do not include the case of RFERS
Temperature changes and soil-structure interaction

- Large changes in temperature will cause expansion and contraction movement of the structure
  - Perpetual soil-structure interaction
- Changes in soil properties due to soil-structure interaction
  - Soil stresses and lateral earth pressure changes
- Soil-structure interaction effects on stresses and deformations in structure
- Effects of soil and structure properties on the behavior of RFERS
Presentation Content

Introduction

Literature Review

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Conclusions and Recommendations

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Earth pressure problem dates back to late 17th century

Coulomb (1773) made a lasting impression after work by many such as Bullet (1691), Couplet (1726, 1727, 1728), Beldior (1729) among others

Coulomb considered the case of a rigid mass sliding upon a shear failure plane

Formed basis for equation to calculate lateral earth-pressure on retaining walls
In 1808 Maniel extended the work of Coulomb and others to give general solution for frictional, non-cohesive soil, with wall friction.

Müller-Breslau (1906) expanded further on Maniel’s work.

General solution for a frictional cohesionless soil that allows for sloping backfill is

\[ Q_a = \frac{1}{2} \gamma H^2 \frac{f_1}{\sin \alpha \cdot \cos \delta} \]

\[ f_1 = \frac{\sin^2(\alpha + \phi) \cdot \cos \delta}{\sin(a - \delta) \cdot \frac{\sin(\phi + \delta) \sin(\phi - \beta)^2}{\sqrt{\sin(\alpha - \delta) \sin(\alpha + \beta)}}} \]
Active Soil Case
Soil Properties:
\[ \gamma, \phi \]
In 1857, Rankine extended on this earth pressure theory by deriving a solution for a complete soil mass in a state of failure.

In 1915, Bell extended Rankine's solution to allow for the effect of soil cohesion.

Following the work of Terzaghi in the early 1920s, and the introduction of the concept of effective stress, the coefficient of earth pressure was defined in terms of effective stress as a function of the shear strength parameters of the soil.
Work continued in the late 1920s and 1930s on the refinement of the earlier analytical solutions for earth.

Observation of excavation reported by Meem (1908) and Moulton (1920) were found to contradict the lateral earth pressure implied by Coulomb solution.

Ohde (1931) and Terzaghi (1941) proposed two relatively complex analyses, neither of which are in much use due to their complexity.
Work Continued on the development and verification of lateral earth pressure theories on retaining walls

- Peck and Ireland (1961)
- Rowe and Peaker (1965)
- Mackey and Kirk (1967)
- James and Bransby (1970)
- Rehman and Broms (1972)
- Coyle et. Al (1972)
- Fang and Ishibashi (1986)
Work continues to date on the refinement of the lateral earth pressure theory but for common retaining wall structures only:
- Gravity and cantilevered retaining walls
- Anchored retaining walls
- Braced retaining walls
- Mechanically stabilized retaining wall
- Cellular cofferdams

No research work has been reported on more complex retaining structures.
On soil-structure interaction due to temperature changes, research work on integral bridge abutments has been reported.
Work on Integral Bridges date back to Broms (1971) who measured lateral earth pressure behind several bridges in Sweden.

- Ingelson (1972)
- Jorgenson (1983)
- Greinman et al. (1986)
- Girton et al. (1991)
- Sandford and Elgaaly (1993)
- Springman and Norrish (1994)
- Fang et al. (1994)
Work Continued

- Thippeswamy et al. (1995)
- Springman et al. (1996)
- Carder and Card (1997)
- Ting et al. (1998)
- Lehane et al. (1999)
- Thomson (1999)
- England et al. (2000)
- Barker et al. (2000, 2001)
- Xu et al. (2003) ...
As of this date, recommendation for the design of integral bridge abutments that accounts for the soil-structure interaction remain empirical.

A multi-story structure with several bays, free on one side, represents a substantially more complex soil-structure interaction problem:

- Role of lateral stiffness of structure
- Role of size and geometry of structure
- Role of temperature range
- Long term behavior