THAYER SCHOOL OF ENGINEERING AT DARTMOUTH

STRUCTURAL ANALYSIS OF EARTH-BAG SYSTEMS

ENGS 88 – Honors Thesis

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Faculty Advisor: Professor Vicki V. May

28th May 2013

engineering.dartmouth.edu

AGENDA

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- Background
- Project Goals
- Design Methodology
- Construction
- Shake Table Testing
- Observations and Results
- Analysis
- Development of CAD Models
- SolidWorks Simulations
- Conclusions
- Recommendations for Future Work
- Acknowledgements

WHAT IS AN “EARTH-BAG SYSTEM?”

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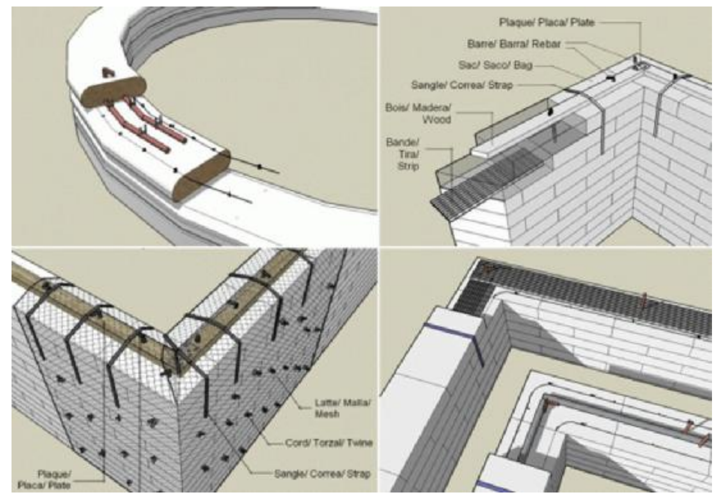
Masonry wall in which the building blocks are earth-bags: sturdy sacks filled with inorganic material (soil).

Reinforcement Techniques:

- Barbed wire is often placed between the courses to improve friction.
- Rebar and twine are hammered in to provide more resistance against overturning.
- Earth-bag walls are finally plastered.

Advantages:

- Inexpensive method to create structures that are both strong and can be quickly built.
- Highly insulated walls with excellent performance in humidity.
- Eco-friendly!
- Provides Greater Resistance to ***Earthquakes***. **(NEED TESTING TO VERIFY THIS CLAIM)**



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EXAMPLES OF EARTH-BAG SYSTEMS

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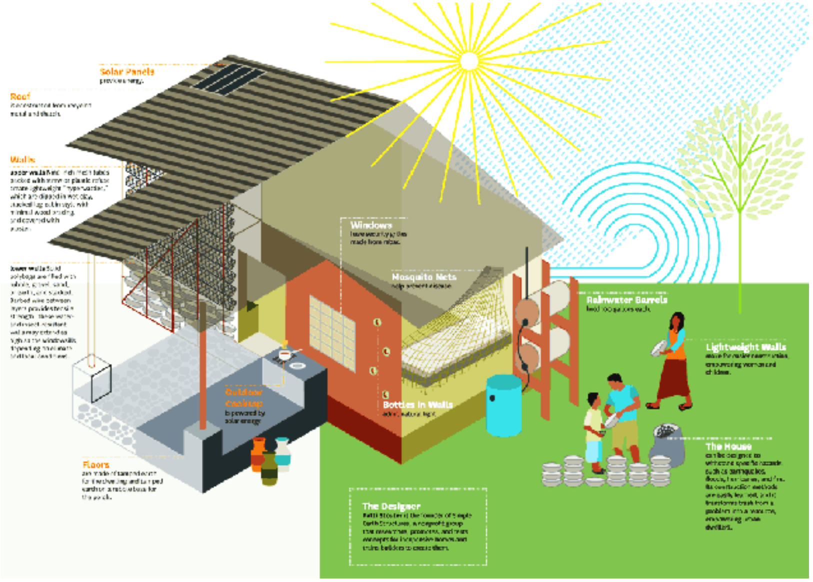
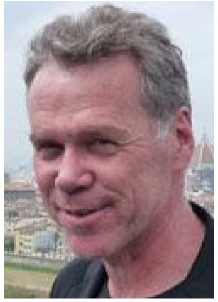
- Historically, earth-bag walls are used as military bunkers and temporary flood controlling dikes.

- Earth-bags are also one of the most popular choices for constructing **affordable housing** in developing countries.

THE $300 HOUSE PROJECT

- Dartmouth's initiative to design and implement affordable housing solutions for Haiti.
- Professor Vicki May is part of a team of designers creating innovative ways to **reduce** construction **costs** and make implementation **simpler**.
- Challenge is to ensure **safety** of proposed structures.
- Prototype houses are being built in Haiti. Team led by Professor **Jack Wilson**.





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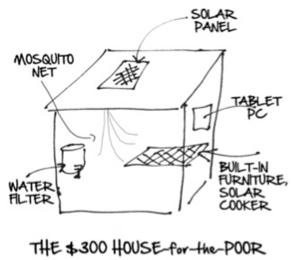
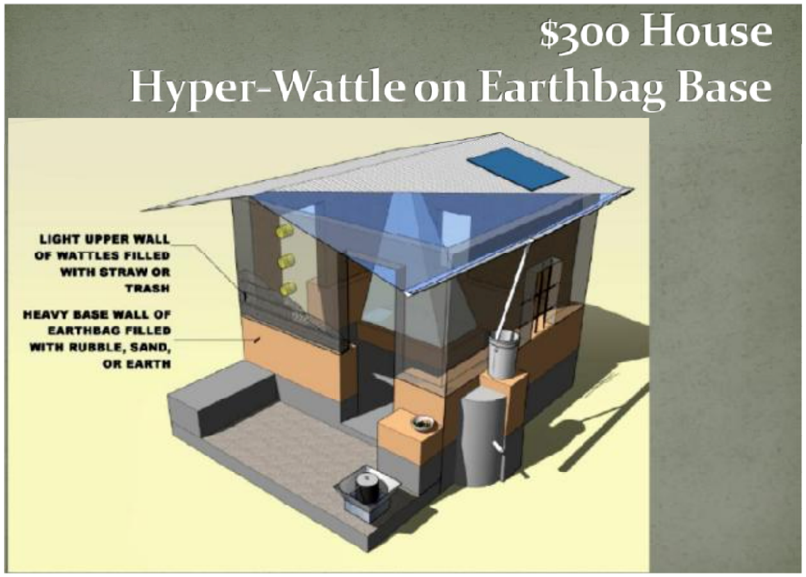
THE $300 HOUSE CHALLENGE

- Blog post in the Harvard Business Review by Professor **Vijay Govindarajan** and Christian Sarkar challenging designers to create a house for the poor, ideally for $300. (http://www.300house.com)
- The Design Challenge winners attended a Design Workshop at Dartmouth in Jan 2012.



Patti Stouter, one of the winners of the $300 House Challenge, is an expert in Earth-bag construction. She gave an ENGS 71 guest lecture emphasizing the need for **experimental testing** of alternate materials.



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ENGS 71 GROUP PROJECT

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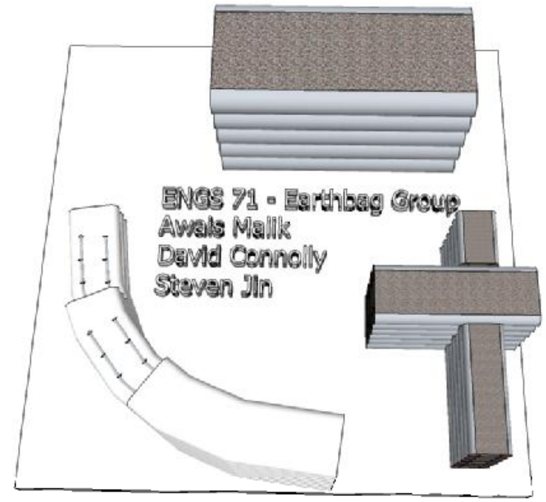
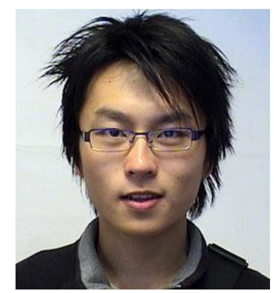
- Professor May presented the $300 House Challenge to her students in ENGS 71 (Structural Analysis) in Spring 2012.
- I was a member of the group investigating the structural viability of earth-bags.



STEP 1 à STEP 2 à STEP 3



David Connolly
‘13



Steven Jin
‘12

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ENGS 71 GROUP PROJECT

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- Our project goal was to investigate the effectiveness of rebar as an added reinforcement.
- We built two walls scaled down to 40%. One wall had rebar hammered through at regular intervals.
- The test setup included a hydraulic jack connected to a force gage. A ruler was fixed along the jack to measure the displacement.
- We measured the in-plane and out-of-plane displacements of each wall.

ENGS 71 GROUP PROJECT

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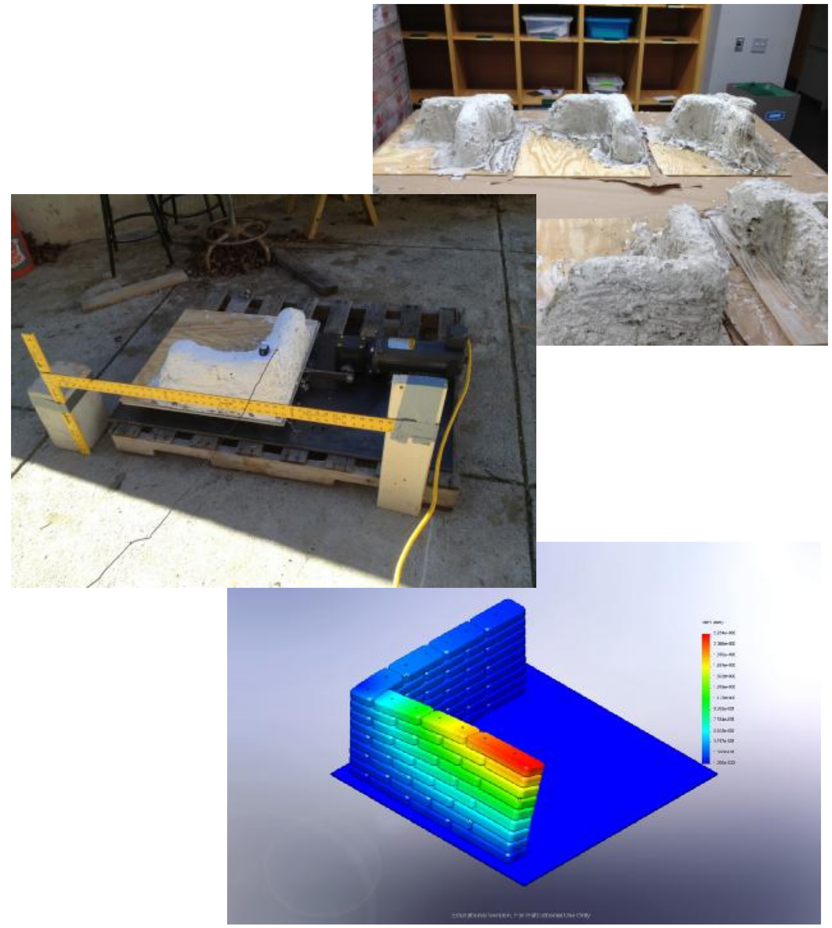
- In order to compare our experimental results with theoretical predictions, we needed to experimentally determine the Young's Modulus of an earth-bag.
- We used the Instron to compress a single earth-bag. The Force vs. Extension data was used to create a Stress – Strain plot.
- The slope of the linear portion of the graph (Young's modulus) was determined to be approx. 20 MPa.
- The wall was modeled as a simply supported beam with maximum deflection at the center of the wall.
- Our test results were **<u>inconclusive</u>** and our experimental readings did not match our predictions.

WE NEEDED A MORE ACCURATE APPROACH TO TESTING.

PROJECT GOALS

- Build scaled down models of earth-bag corner walls (regular corners, piers and buttresses).
- Test effectiveness of reinforcing corners using a **<u>shake table</u>**.
- Measure real-time deformations of the walls up to failure and scale back up to determine the deformations of real-life structures. Compare max. displacements with theoretical predictions.
- Develop a CAD model of the walls and use SolidWorks Simulation to determine the max. deflections in each type of corner wall.



Background **è** ***Project Goals*** **è** Design Methodology **è** Construction **è** Testing **è** Results **è** Analysis **è** SolidWorks **è** Conclusions **è** Future Recommendations

DESIGN METHODOLOGY

- **Ian Herrick** '13 built a shake table for Professor May during the Summer 2012 term. The weight limit of the table determined the scale factor of the corner walls.
- Max. Weight allowed was approx. 100 lbs. The appropriate scale factor was 1/6th of the real-life wall.
- I built two walls of each corner type. The wall dimensions were 20 x 20 square inches.
- Each bag was 2.5 inches wide, and the length of the bags varied from 5 inches to 15 inches depending on location and type of corner wall.
- 1/8th in. thick 24 x 24 in^2 sheets of plywood were used as the base of the walls.
- The total weight of each wall was calculated to be between 50 – 60 lbs.

<u>Shake Table Specifications:</u>
Total travel: 1.4 inches
Table Dimensions: 24 in. by 24 in.
Total Weight: 325 lbs.
Weight Limit for Testing: 100 lbs.
Frequency Range: 0 Hz to 5.8 Hz
Motor: Baldor 0.5 HP, 90 V, DC Gear

DESIGN METHODOLOGY

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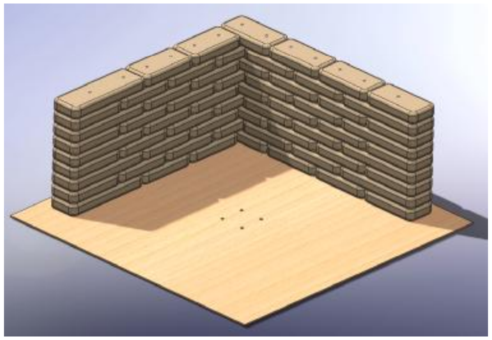
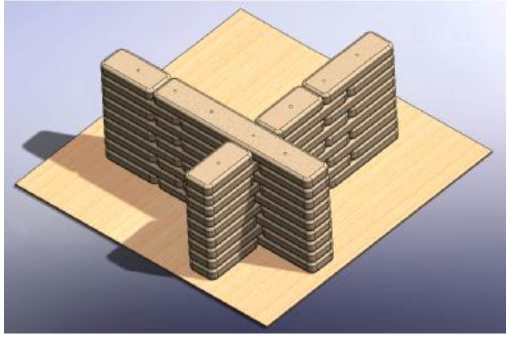
The Curious Case of scaled down models!

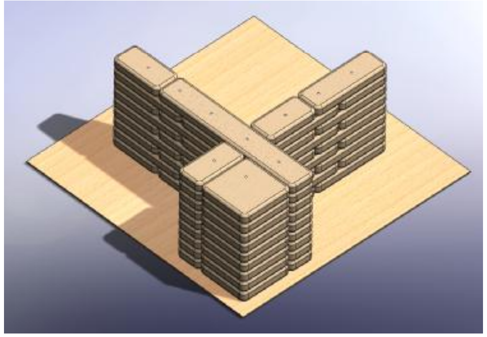
- The earth-bags were not the only parts of the model that needed scaling.
- Barbed wire and rebar also needed to be scaled down.
- Required barbed wire diameter = 0.06 in.
- Required rebar diameter = 0.2 in.



Regular Corner



Pier



Buttress

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CORNER WALLS CONSTRUCTION

Getting the right soil (Ball Drop Test)

- Wet soil just enough to hold together. Form into 4 cm (1.5 inch) diameter balls.
- Drop them from 1.5 m (5') height onto a hard surface. If they flatten only slightly the soil has too much clay and needs more sand.
- If the balls develop cracks (break into 4 or 5 pieces), the soil is good for earth-bags.
- If the balls shatter, the soil does not have enough clay or moisture.

Plastering (2-layer Process)

- Layer 1: Mixture of Soil and Straw
  - Ø Provides a rough, flat surface on which the plaster can stick and harden easily.
- Layer 2: Plaster of Paris
  - Ø Used a 2:1 ratio of water to plaster.

CORNER WALLS CONSTRUCTION

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Shouldn't building a smaller model be easier?

- Answer: Yes and No.
- Less labor-intensive, but more time-intensive.
- The polypropylene woven bags needed to be cut down to size and then stitched to form a bag. (Time sink. The sewing machine kept breaking down!)
- I had to use a tablespoon to fill each bag, and the handle end of a hammer for tamping the soil firmly inside the bags. (Another time sink!)
- The 0.06 in. diameter wire had to be cut into barbed pieces using a wire cutter. (Yet another time sink!)
- Took me 6 weeks to build 6 walls!

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SHAKE TABLE TESTING

- Testing took place on November 20th, 2012.
- Conducted by Awais Malik and Ian Herrick.
- The wooden base of the walls were bolted to the shake table.
- One side of the corner walls was perpendicular to the direction of motion. The other side was parallel.
- Two 3-axis accelerometers were fixed on to the top of the walls.
- A high-speed camera was also set up to measure displacement of a fiducial point.
- However, memory storage became an issue. The camera could take continuous snapshots for only 1 minute. Our experimental requirement was at least 5 minutes, so we could not use the camera.
- Initial shaking frequency was 1.5 Hz with an incremental increase of 0.5 Hz after every minute until failure.

OBSERVATIONS & RESULTS

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Observations:

- Both the regular corners failed at a shaking frequency of 4.0 Hz. Failure occurred at the corners.
- The piers were slightly more resistant than regular corners. One wall failed at 4.5 Hz. The other at 4 Hz. Failure did NOT occur at the corner.
- Both buttresses failed at 4.0 Hz. The wall remained intact as the outer column fell off.

Regular Corner

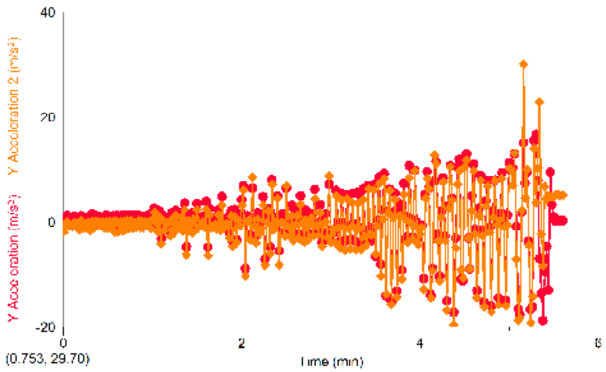
Pier

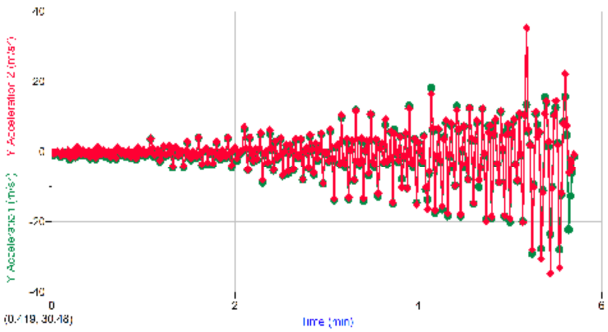
Buttress

ACCELEROMETER RESULTS

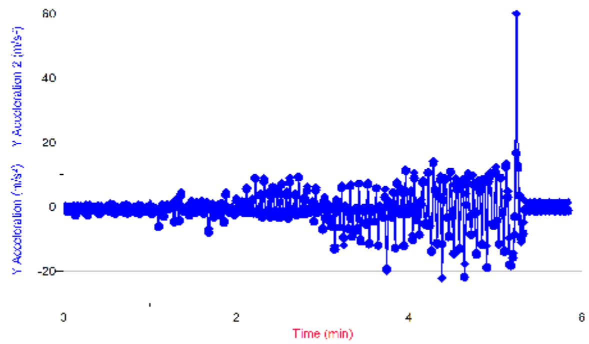
Acceleration vs. Time Plots

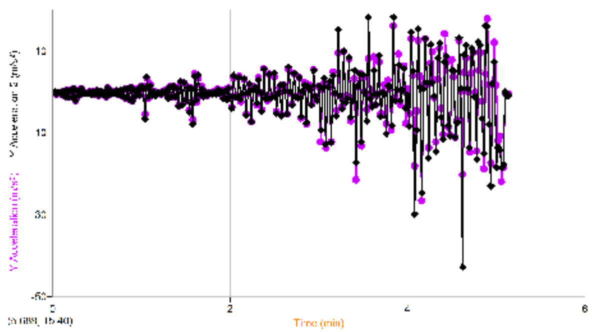
Regular Walls



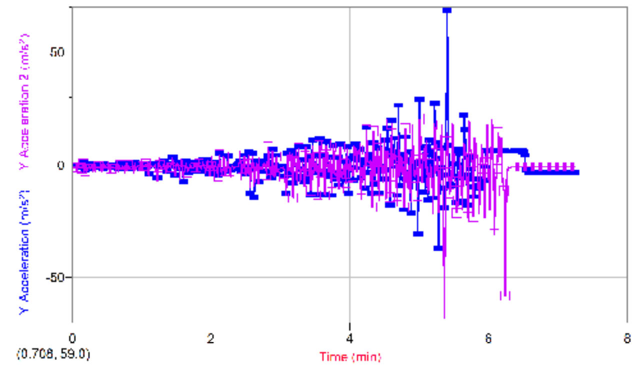


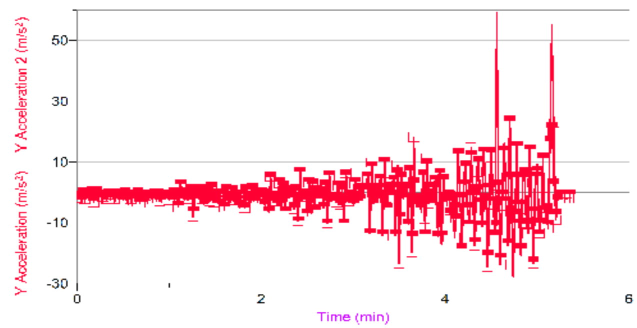
Piers





Buttresses





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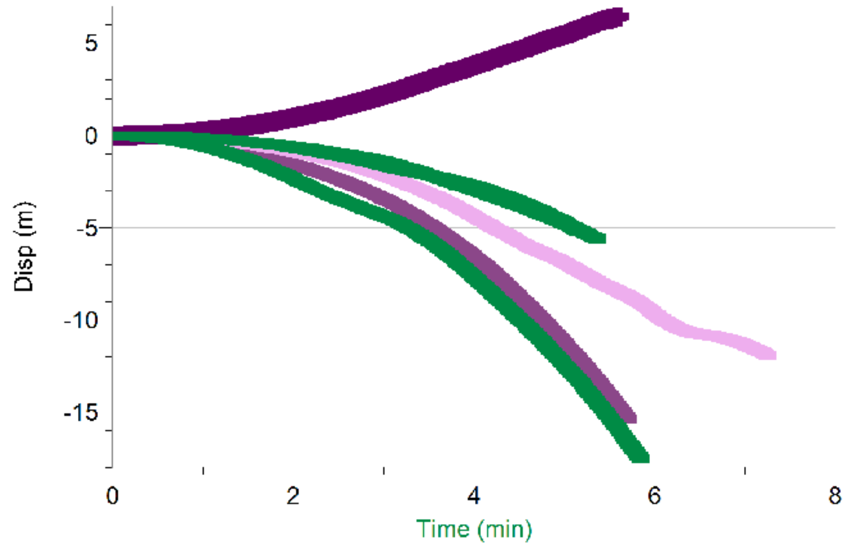
ANALYSIS OF TEST RESULTS

Displacement vs. Time Plots



This data needs to be corrected!

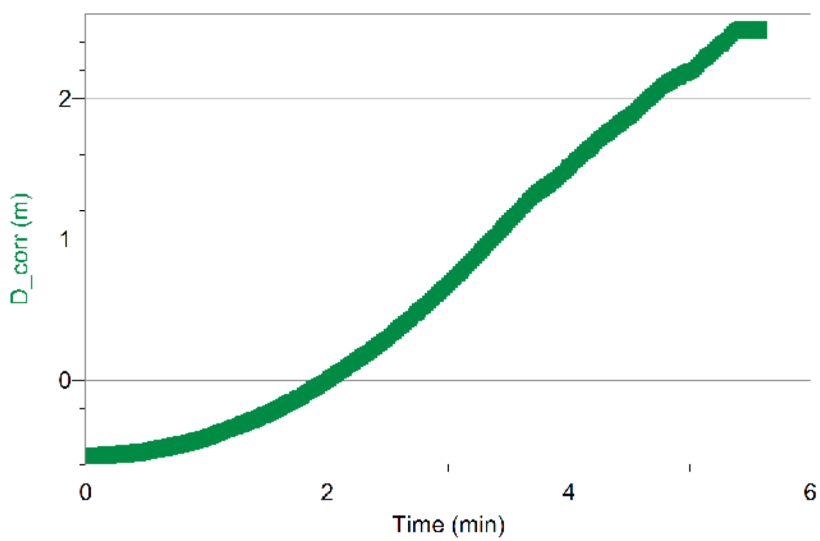
Houston, we have a problem!

- The displacement graphs should be sinusoidal, not exponential!
- Problem lies in the use of accelerometers. Very difficult to extract displacement from acceleration.
- The slightest of offsets will make the accelerometer think that the wall is moving continuously in a certain direction instead of oscillating back and forth.

ANALYSIS OF TEST RESULTS

Correction Attempt

- Subtracted the mean displacement from each individual displacement reading.
- Improves the readings slightly, but still no where near predicted results.
- Developing an algorithm to produce an accurate set of displacement data is an Honors thesis project in itself.



Regular Wall 1

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THEORETICAL PREDICTION

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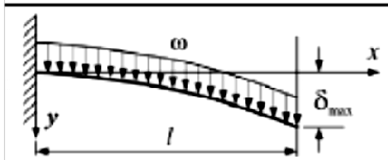
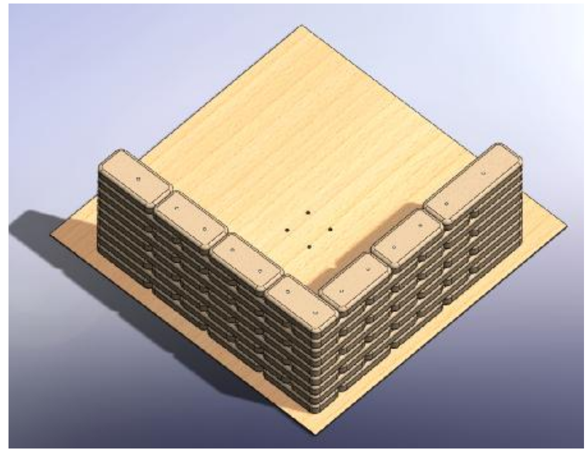
- **Model the side of the wall perpendicular to the direction of motion as a Cantilever beam. Assume the wall parallel to the direction of motion acts as a fixed support.**

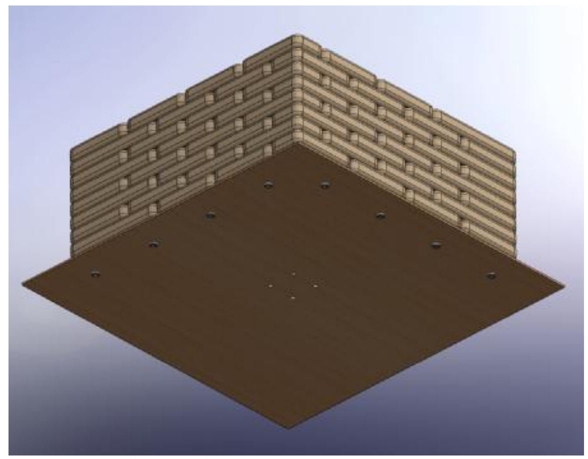
3. Cantilever Beam – Uniformly distributed load ω (N/m)			
	$\theta = \frac{\omega l^3}{6EI}$	$y = \frac{\omega x^2}{24EI}(x^2 + 6l^2 - 4lx)$	$\delta_{max} = \frac{\omega l^4}{8EI}$
	Slope at free end	Deflection at length, x, away from fixed end	Max. Deflection at free end

- **Force = mass x acceleration = 255.0 N; mass = 50 lbs. / 2 = 25 lbs. = 11.34 kg; acceleration = $4\pi^2 f^2 x$ = 22.49 m/s²**
  (Frequency, f = 4.0 Hz; Distance, x = 1.4 inches = 0.0356 m)
- Distributed load, $\omega = \frac{Force}{length} = \frac{255\ N}{0.445\ m} = 573.0\frac{N}{m}$
- Young's Modulus, E = $2.0\text{x}10^7$ Pa
- Moment of Inertia, I = $\frac{bh^3}{12} = \frac{2.5*9^3}{12} = 151.875\ inch^4 = 6.3215*10^{-5}\ m^4$
- Maximum deflection, $\delta_{MAX} = \frac{\omega l^4}{8EI} = 2.22\ mm$

DEVELOPMENT OF CAD MODELS

- SolidWorks: the final frontier! 3D Mechanical CAD modeling software with powerful simulation tools.
- The earth-bags were modeled as rectangular bars with fillets on each edge.
- A custom material was created and applied to the earth-bag extrudes.
- Used cylindrical pins as barbs that fitted into extruded cuts in between each earth-bag row.
- However, SolidWorks detected interferences as a result of the Pattern feature on the cuts.
- If SolidWorks detects any interference, it cannot create a mesh for simulation.
- As an adjustment, I removed the barbs and their respective extruded cuts, and replaced them with rebar.
- Now a very fine mesh was formed, and the finite element analysis (FEA simulation) could run.





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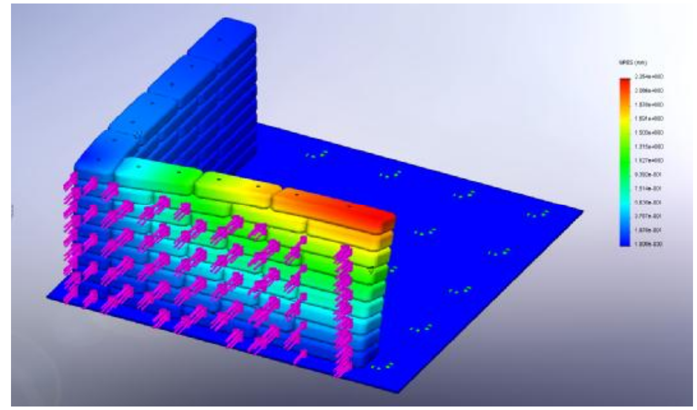
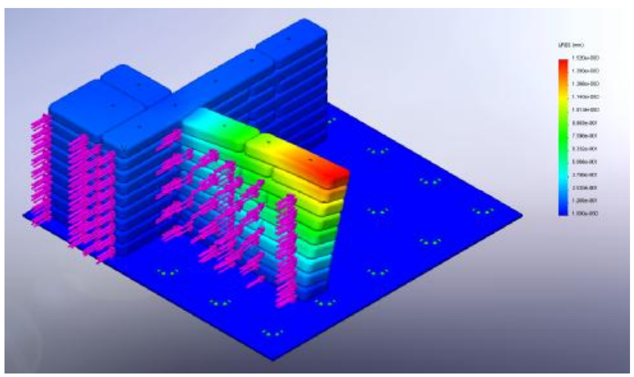
SOLIDWORKS SIMULATIONS

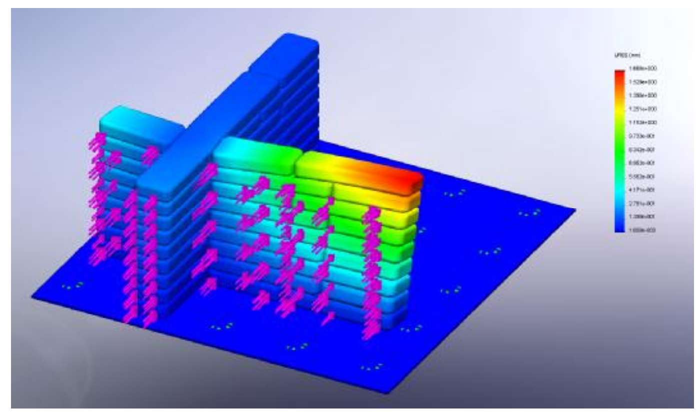
Maximum Deflections:

- Regular Corner – 2.254 mm
  Real-life wall – 13.52 mm
- Piers – 1.668 mm (26% decrease)
  Real-life wall – 10.00 mm
- Buttresses – 1.520 mm (33% decrease)
  Real-life wall – 9.12 mm

SolidWorks Simulations and Theoretical Predictions match up very well! (1.5% error)







CONCLUSIONS

- Corner reinforcements increase the wall's resistance to vibration (higher failure frequency and lower max. deflection), and are worth the added investment.
- The SolidWorks models and the cantilever beam model should be accurate predictors of the behavior of earth-bag systems under earthquake conditions.

FUTURE RECOMMENDATIONS

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- Larger scale testing to obtain more accurate failure modes of real-life structures.
- Use **Motion Detectors** that measure distance directly in place of accelerometers.
- Reinforce the stub ends of the walls with meshing.
- Ensure earth-bag edges do NOT **line up**.
- Do such projects as part of a GROUP!

ACKNOWLEDGEMENTS

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- Ian Herrick
- David Connolly
- Steven Jin

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THANK YOU!

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Questions?

Comments?