BENEFITS OF NON-LINEAR BEHAVIOR IN THE SEISMIC RESPONSE OF WATER STORAGE TANKS

by

Allan R. Porush, S.E.

URS CORPORATION

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WATER STORAGE TANK

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Location:	**Yorba Linda, California, Near Whittier-Elsinore Fault Zone**
Size:	**60 feet diameter, 80 feet high**
Shell thickness:	**varies from 1 1/8 inch to ¼ inch**
Anchor bolts:	**67 bolts, 2-1/2 inch diameter x 5 feet long**

WATER STORAGE TANK – PILE FOUNDATION

-70 foot octagonal pile cap, 5 feet thick

- 97 piles, 2-1/2 feet diameter x 30 feet long w/ 6 foot bell, arranged in 11 rows

- piles reinforced with 5 #7 bars each

- pile cap reinforced (lightly) w/ #7 @ 18” top and #11 @ 9.5” bottom

INITIAL CONVENTIONAL LINEAR ANALYSIS

475 - year Site-Specific Spectrum
(PGA = 0.72g)

AWWA D-100-96 (1998)
"R" factor of 4.0

Apparent Deficiencies

Anchor Bolts overstressed by factor of 2+

Overstress in Shell

Piles Overstressed

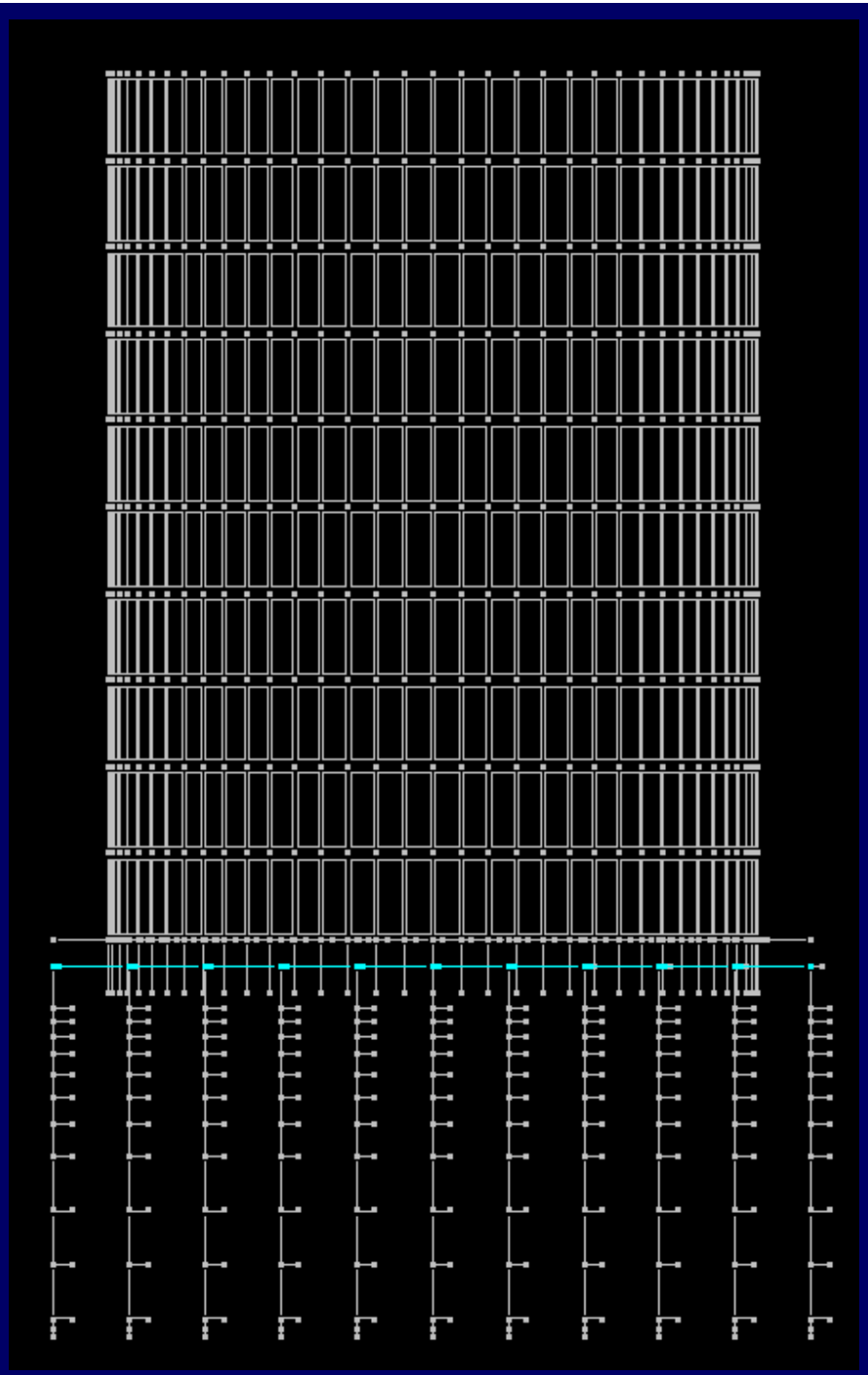
DECISION TO TRY NON-LINEAR "PUSH-OVER" ANALYSIS

3-D non-linear model: 2,000 nodes, 12,000 D.O.F

Non-linear model elements:

- Anchor bolts: tension (and shear)
- Piles: tension, compression and flexure
- Pile cap reinforcing steel: T & B
- Soil: lateral - p-y curves on piles and passive on cap
- Friction under tank bottom

MATHEMATICAL MODEL



PUSH-OVER LOADING + BASIS FOR ANALYSIS

Site-Specific Spectrum -- 10 percent in 50 years

Loading: Housner pressure distribution for Push-over
From TID 7024 -- Both Horizontal and Vertical
Convective (Sloshing) + Impulsive – Added
Impulsive pressure at Peak of Spectrum

"Push" until "target displacement":
Target -- Based on Extension of Linear Analysis.
Target Displ. taken as 1.5 x Linear Displacement

Computer System: PERFORM 3-D

Run time: > 48 hours.

WHY NOT TIME HISTORY?

- Uncertainty and difficulty in modeling fluid mass
- Difficulty in interpreting results
- Great variations with time history record in non-linear
- Requires multiple ground motion records
- Run time

TWO MODELING ASSUMPTIONS

1. Model "A" - anchor bolts do not take shear

   Friction alone transfers base shear to pile cap

   Tank slides

2. Model "B" - anchor bolts take shear

   Tank base shear is resisted by both friction and anchor bolts in shear

   Tank does not slide

RESULTS

Both Models:

- **Push-over curve is stable, monotonically increasing, to target displacement and beyond**
- **Distributed ductility demand**
- **Moderate levels of post-yield strain in anchor bolts, pile steel and pile cap steel (negative moment); also soil yielding**
- **Shell compression stress within nominal ultimate (no "elephant's foot" buckling)**

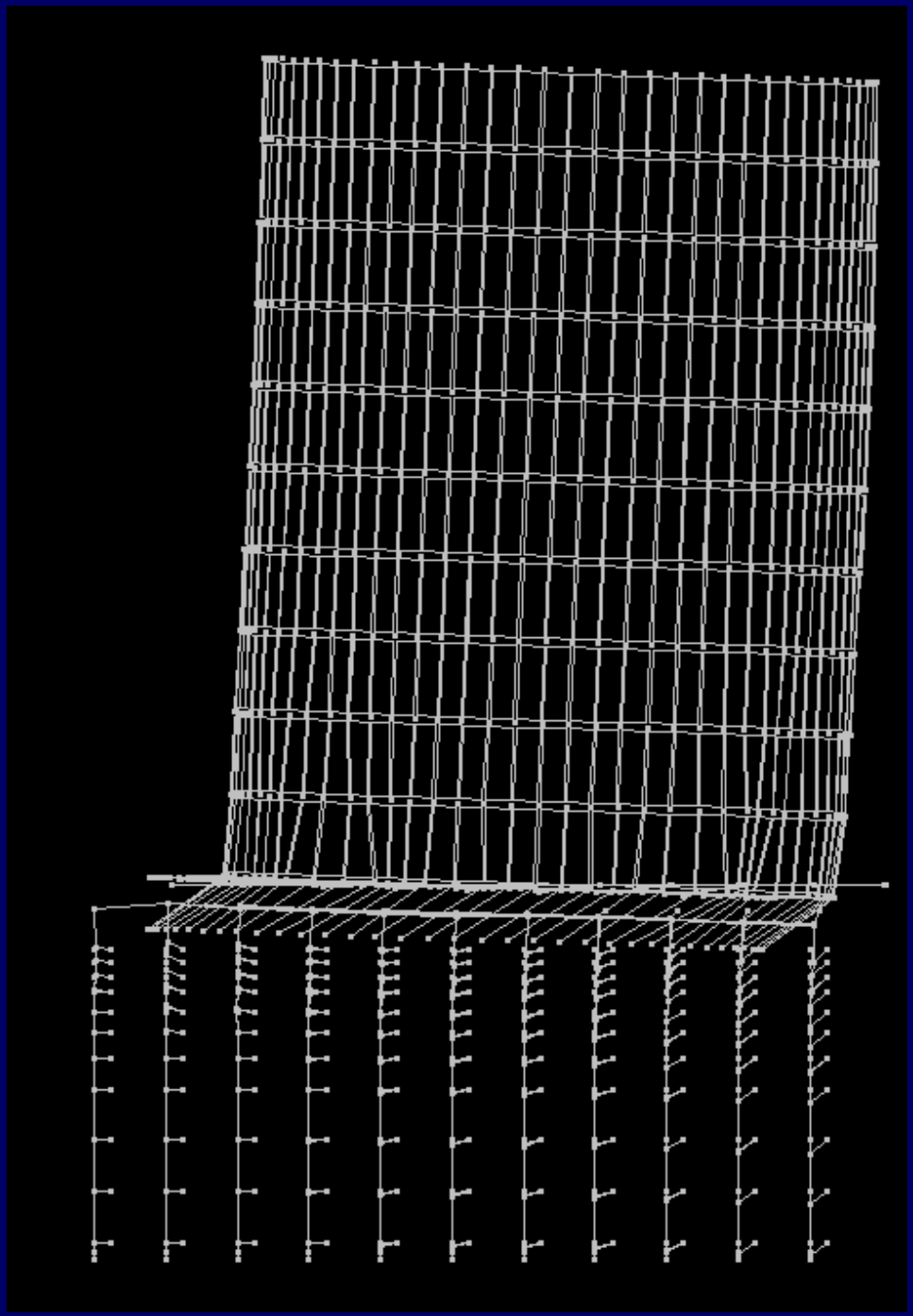
RESULTS -- Continued

Model A (sliding):

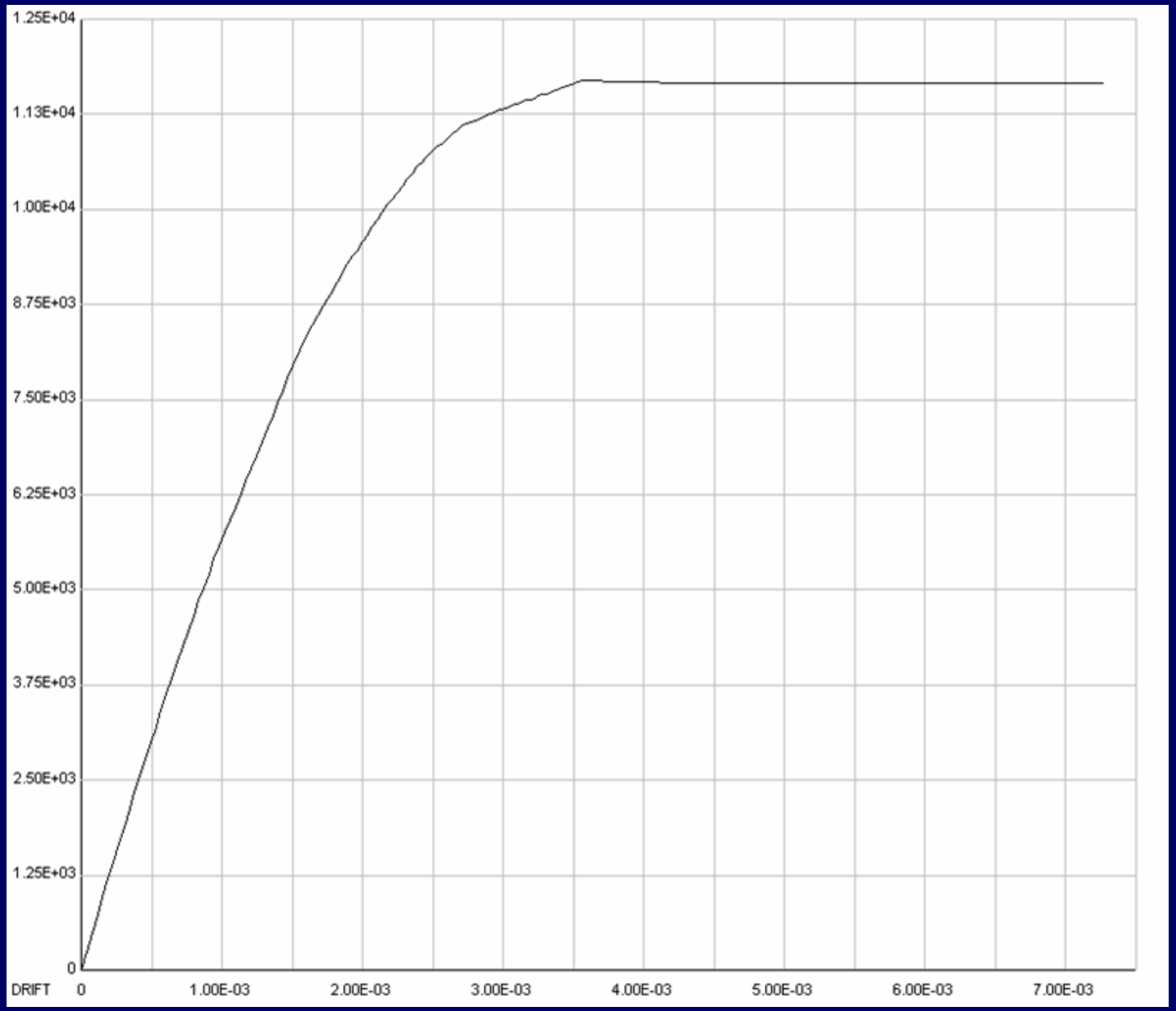
- **Target displacement at top of tank = 7 inches**
- **Sliding displacement = 2.9 inches. Acceptable??**
- **Base Shear = 11,700 kips = 0.84 W**
- **Sliding / friction acts as a partial "fuse"**
- **Peak shell compression stress D / C = 0.70**

MODEL "A"

DEFLECTED SHAPE



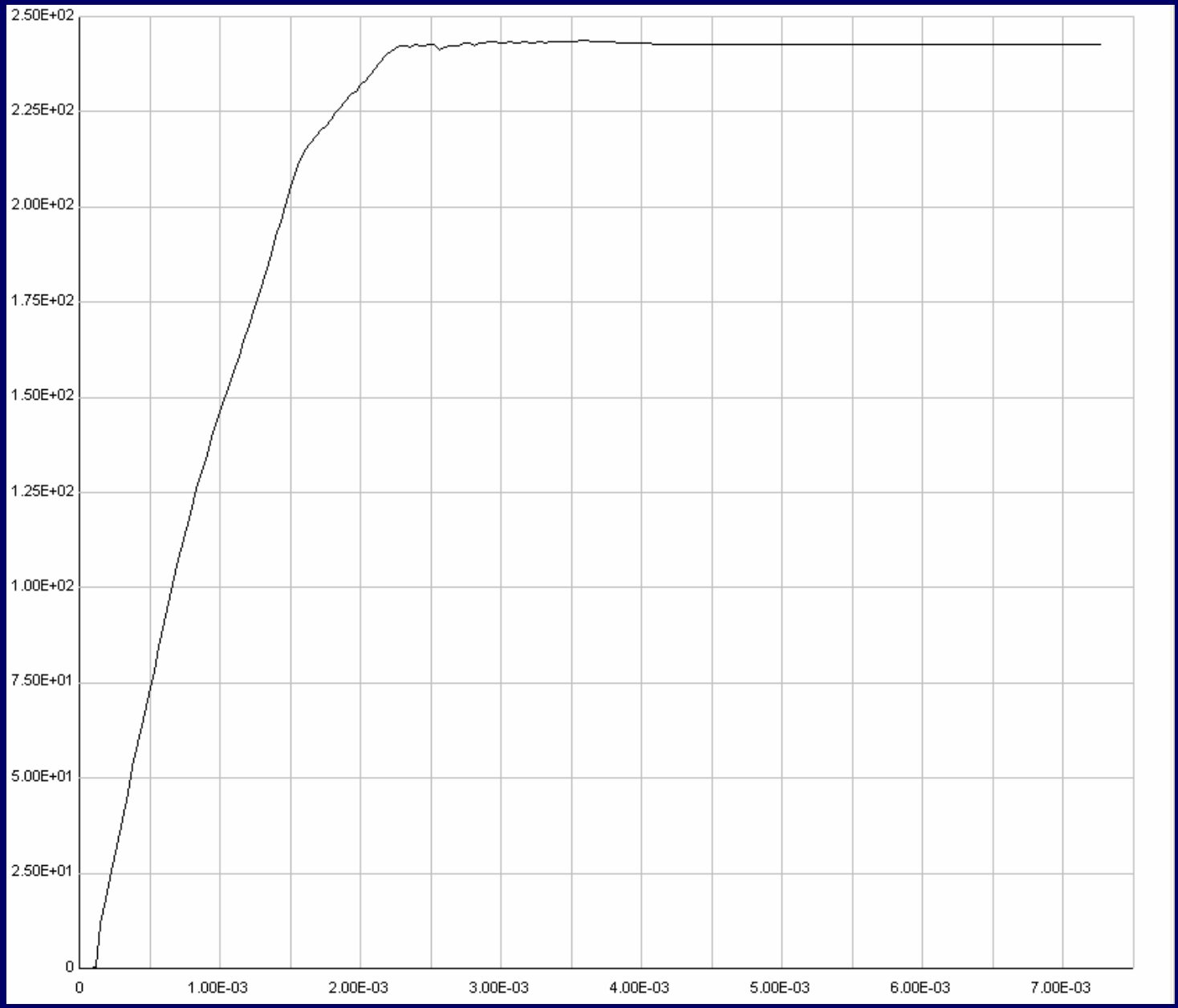
MODEL “A” PUSH-OVER CURVE



BASE SHEAR (kip)

REFERENCE DRIFT (in)

MODEL "A" ANCHOR BOLT TENSION



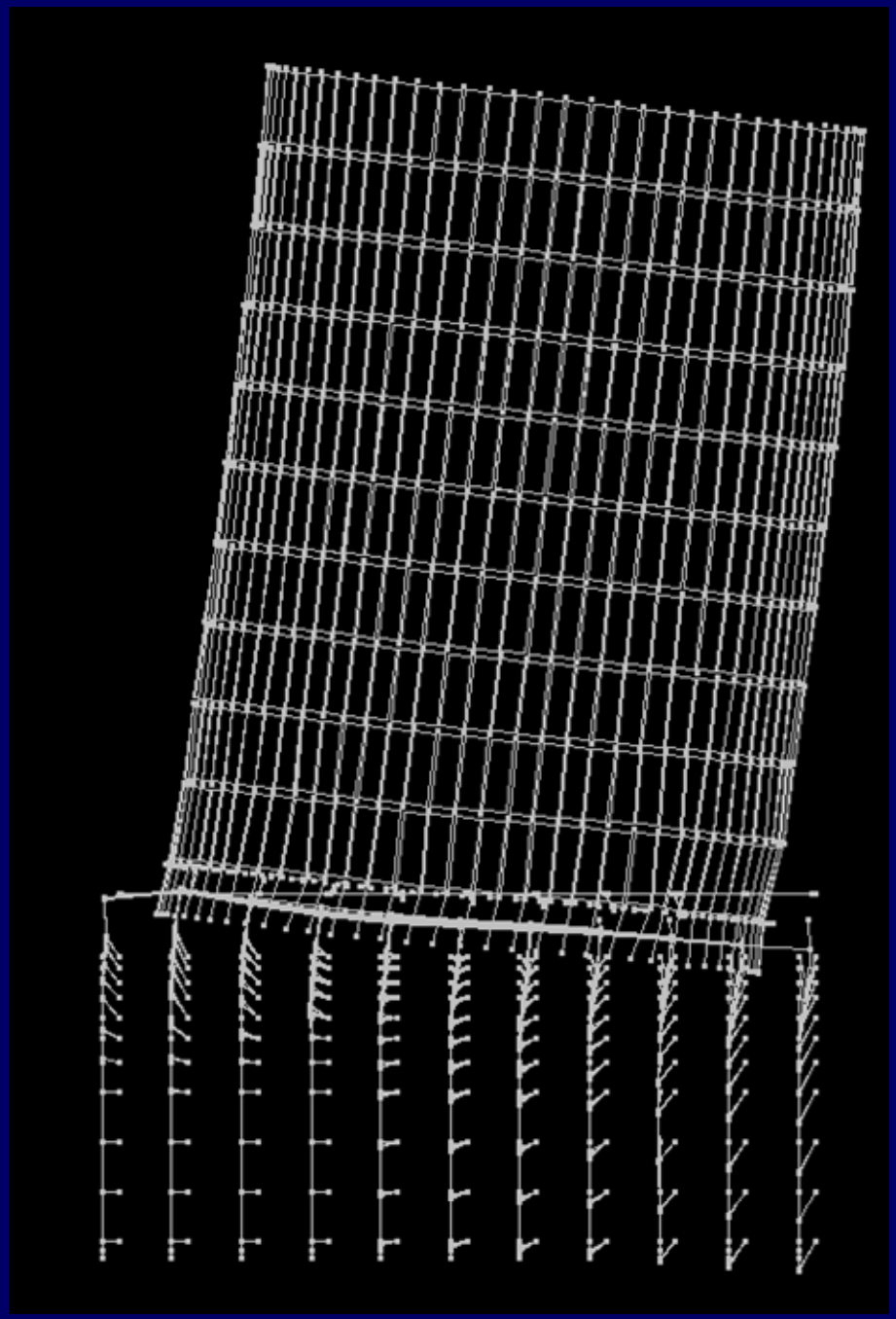
RESULTS -- Continued

Model B (without sliding):

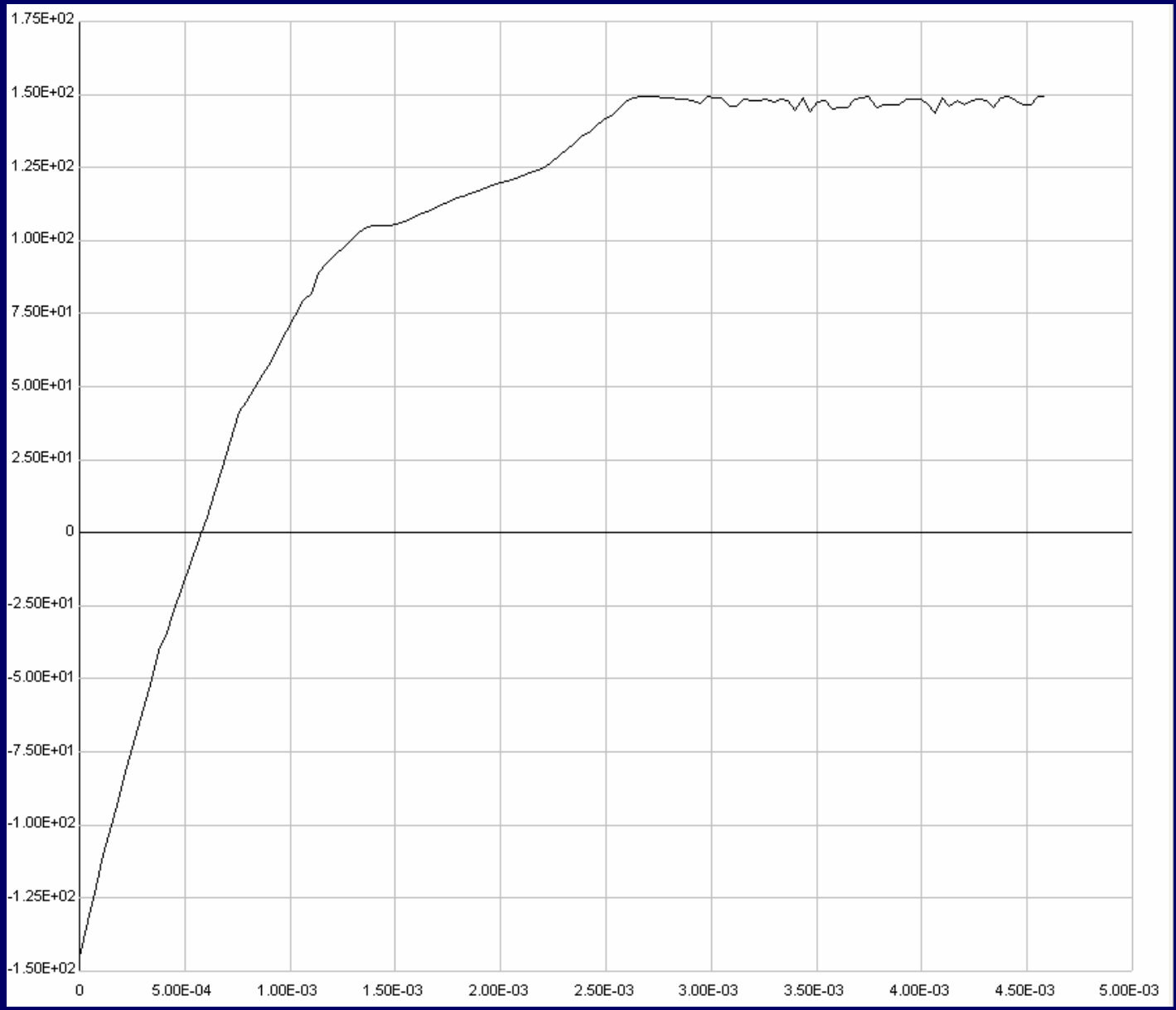
- **Target displacement at top of tank = 6.3 inches**
- **Base shear = 13,700 = 0.98 W**
- **Anchor bolt stretch = 1 / 4 inch**
- **Strain in mat top steel reaches 0.2 %**
- **Peak shell compression stress D / C = 0.85**

MODEL “B”

DEFLECTED SHAPE



MODEL “B” ANCHOR BOLT TENSION



PRELIMINARY CONCLUSION

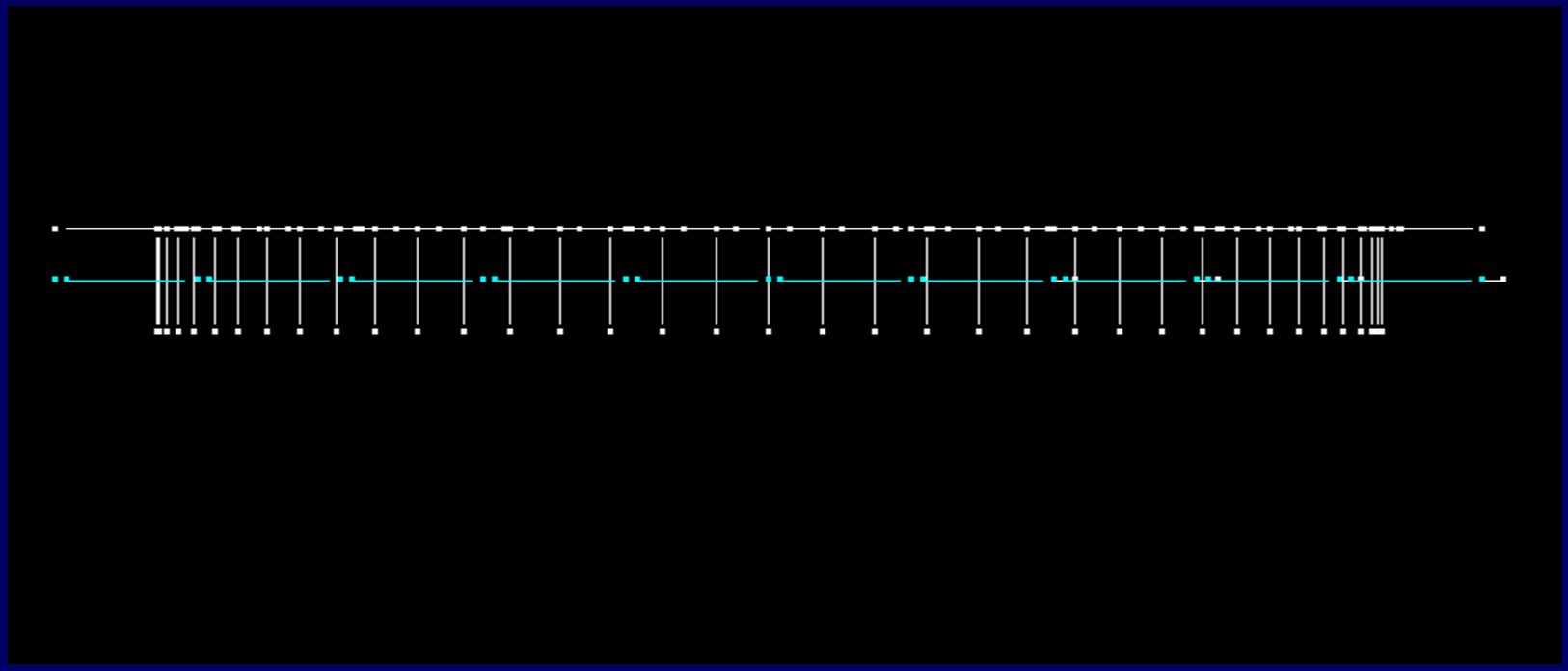
Tank is stable and will maintain its structural integrity (including continuing to hold its contents) for a 475-year earthquake.

No retrofit is required, with the possible exception of providing shear resistance at tank base.

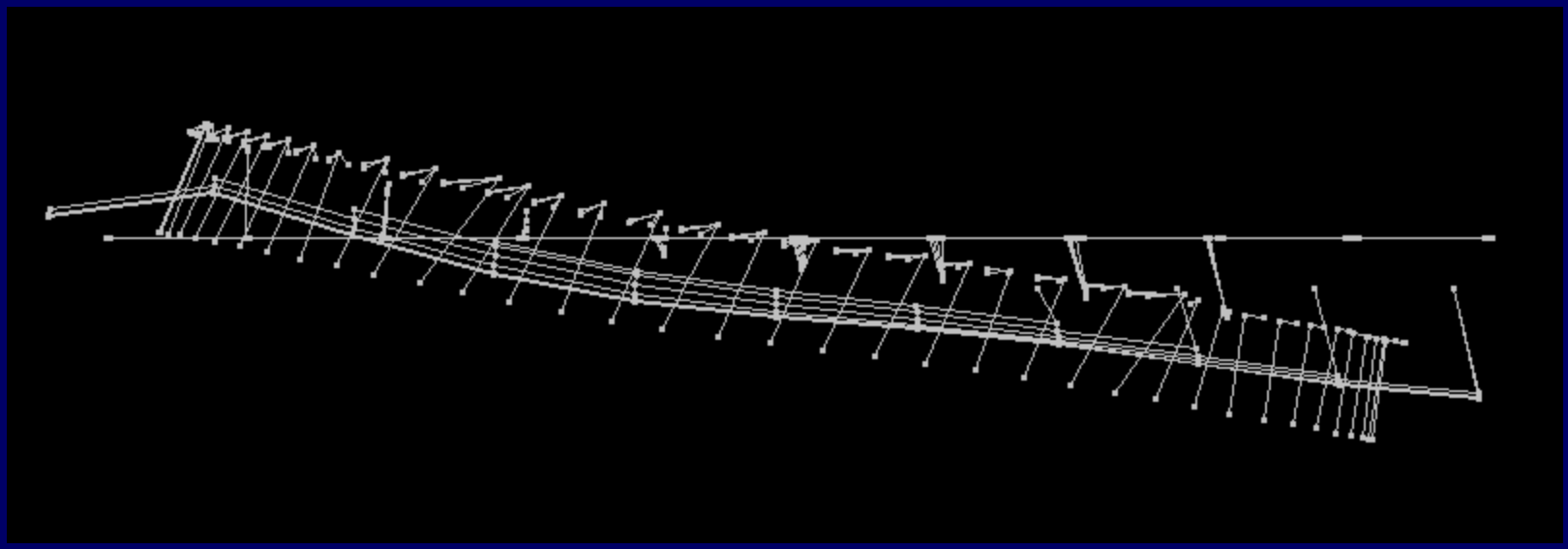
Tank configuration provides ductile behavior in almost all elements.

ISSUES FOR RESEARCH AND CONTEMPLATION

1. Applicability of push-over procedure and "target displacements" to liquid storage tank.
2. Increase factor for target displacement over static displacement (Used 1.5 as composite factor).
3. Sliding -
   Is it real??
   Is it acceptable? (anchor bolts, piping, etc.)
   Does sliding contribute directly to target displacement?
4. Will tanks designed by standard linear analysis methods with ductile elements *generally* prove to have sufficient ability to resist strong earthquake ground shaking?



PILE CAP MODEL



PILE CAP DEFLECTED SHAPE

(MODEL “B”)