Three Dimensional Numerical Simulations of Residential Buildings on Expansive Soils

By

Robert L. Lytton, Xiong Zhang and Rifat Bulut

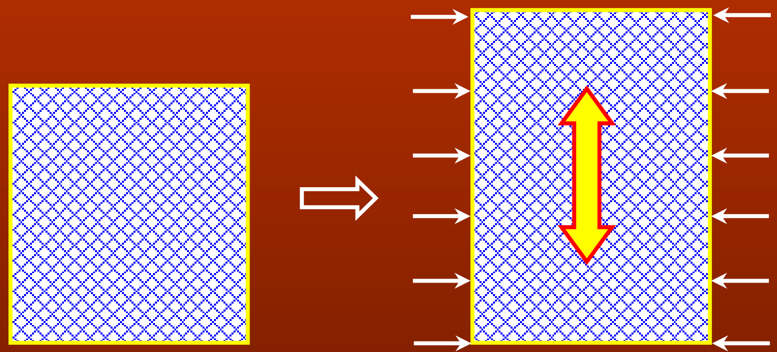
Department of Civil Engineering

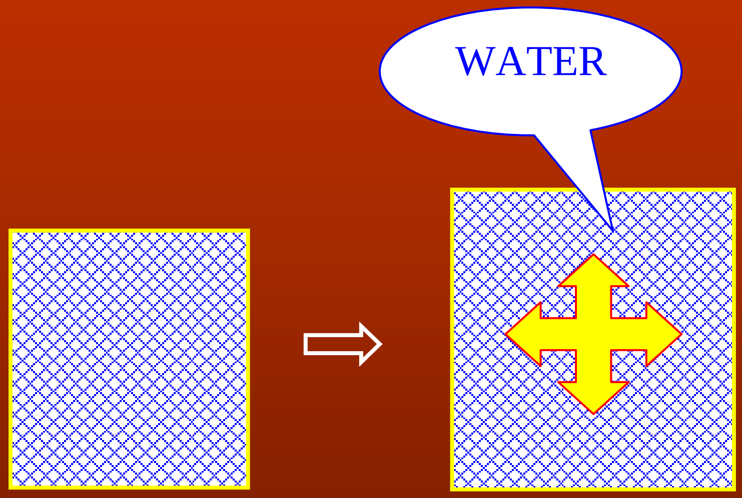
Texas A&M University

OUTLINE

- INTRODUCTION
- MODELS NEEDED FOR SIMULATION
- LABORATORY TESTS
- VERIFICATION OF THE PROPOSED METHOD
- NUMERICAL SIMULATIONS OF RESIDENTIAL BUILDINGS ON EXPANSIVE SOILS
- CONCLUSIONS

FACTORS INFLUENCING THE VOLUME OF EXPANSIVE SOILS



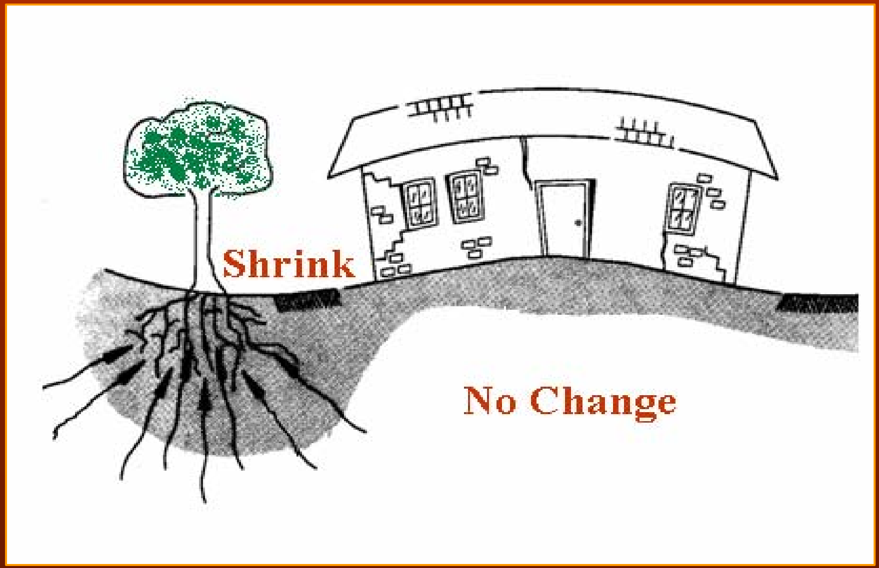


MECHANICAL STRESS

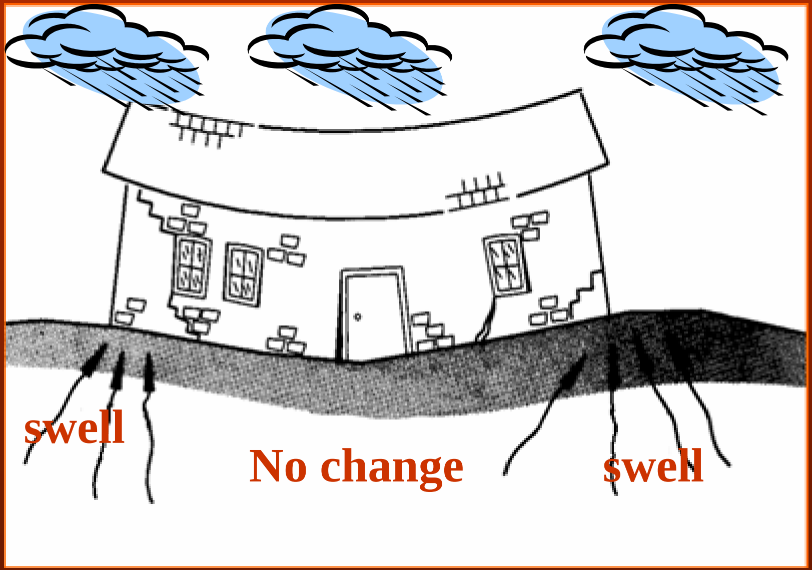
MATRIC SUCTION

TYPICAL DAMAGE CAUSED BY EXPANSIVE SOILS

SUMMER

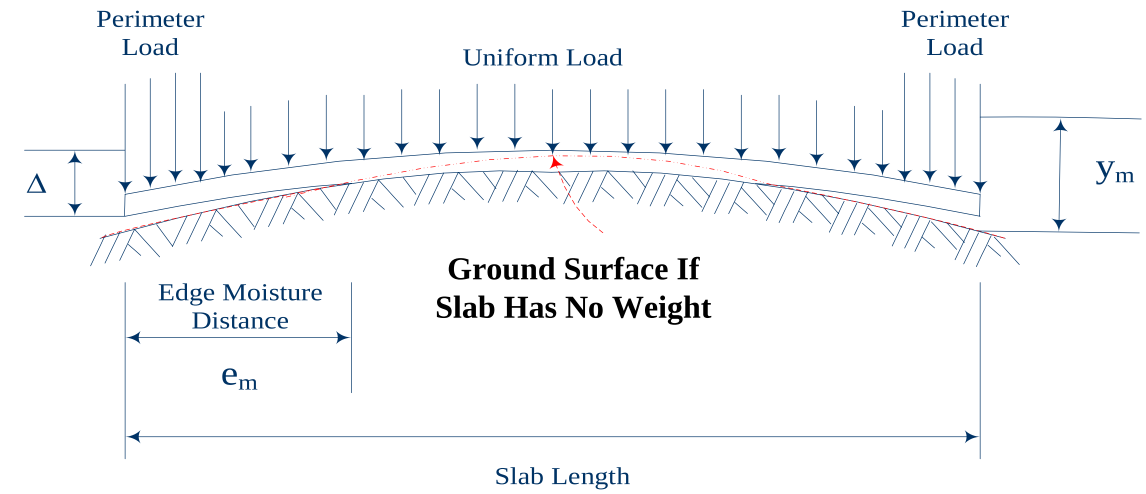


WINTER

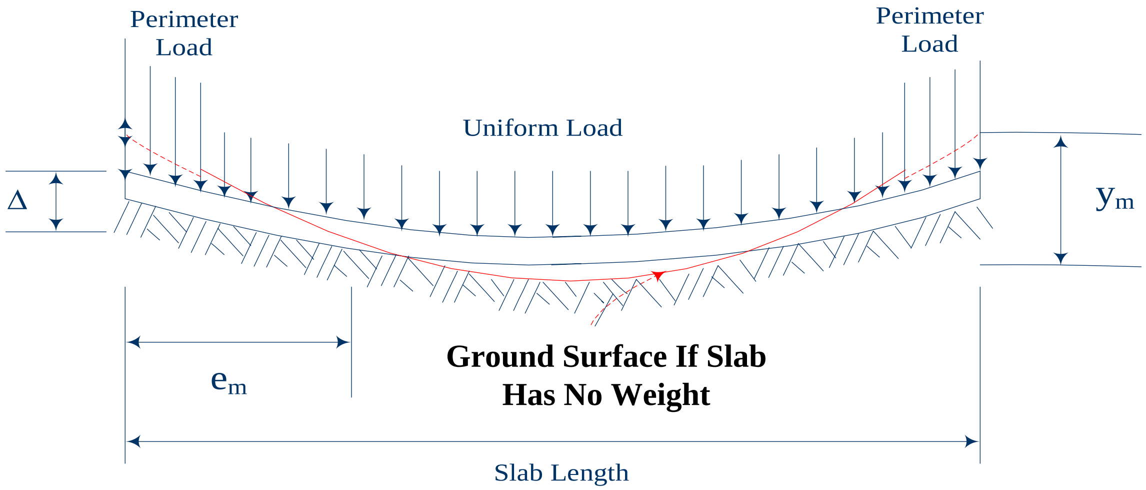


*** MODIFIED FROM WRAY (1995)**

DAMAGE MODES FOR SLAB ON EXPANSIVE SOILS



(a) Center lift (or Edge drop) case



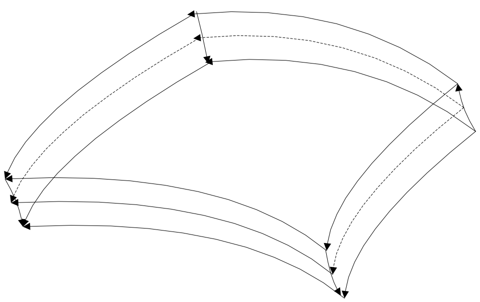
(b) Edge lift (or Center drop) case

SIGNIFICANCE OF THE RESEARCH

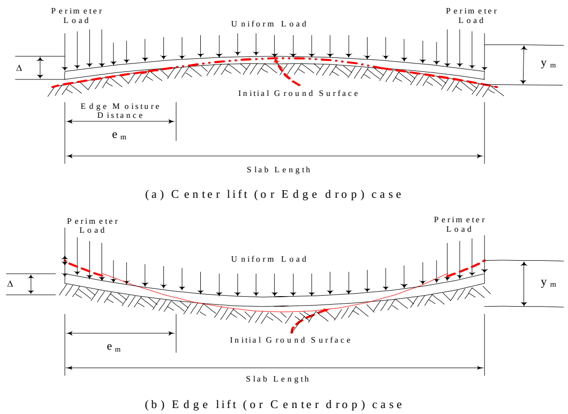
1. JONES AND HOLTZ (1973): $2.2 BILLION/YEAR
2. KROHN AND SLOSSON (1980): $7.0 BILLION/YEAR
3. JONES AND JONES (1987): $9.0 BILLION/YEAR---MORE THAN TWICE THE COMBINED DAMAGE FROM EARTHQUAKE, FLOODS, TORNADOS AND HURRICANES
4. WRAY (1989): 8,470 RESIDENTIAL FOUNDATION FAILURES IN ONLY ONE YEAR IN DALLAS COUNTY, TEXAS, 98% OF WHICH OCCURRED IN EXPANSIVE SOILS

MODELS NEEDED FOR THE SIMULATIONS

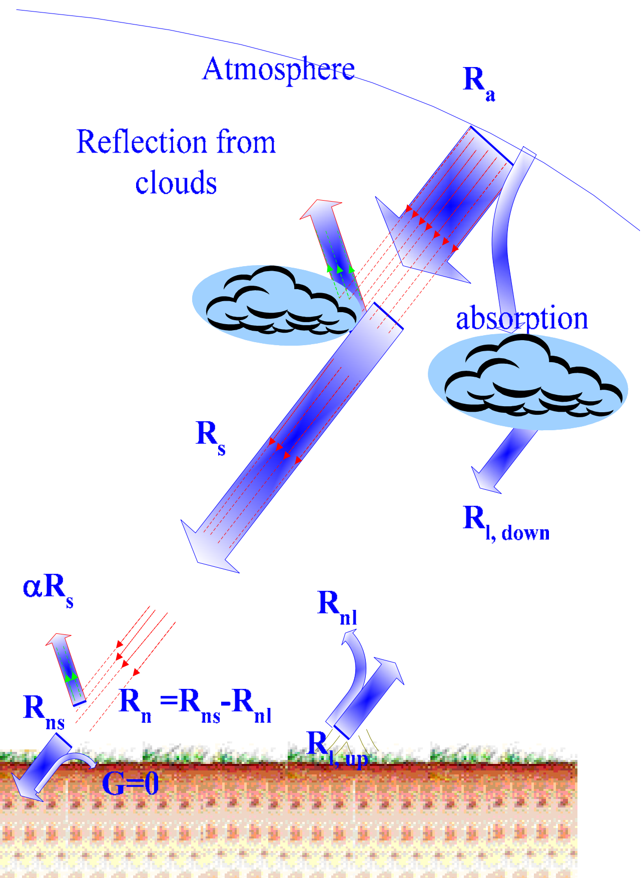
4. Shell elements for walls



3. Soil-structure interaction



2. Evaporation & transpiration



5. Damages in the walls

1. Coupled consolidation theory for saturated and unsaturated soils

MODELS NEEDED FOR THE SIMULATIONS

- **COUPLED HYDRO-MECHANICAL STRESS ANALYSIS**

  -----VOLUME CHANGE OF EXPANSIVE SOILS

- **ESTIMATION OF EVAPOTRANSPIRATION AND INFILTRATION**

  -----INFLUENCE OF WEATHER AND VEGETATION (WATERING)

- **SOIL-STRUCTURE INTERACTION**

  -------SHEAR, SLIP AND SEPARATION BETWEEN SOIL AND SLAB

- **SIMULATION OF SLABS AND WALLS**

  -------MOMENTS AND STRESSES IN THE WALL AND SLAB

- **CRACKING MODEL**

  --------DAMAGES TO THE STRUCTURE

GOVERNING DIFFERENTIAL EQUATIONS

$$\frac{\partial(\sigma_x - u_a)}{\partial x} + \frac{\partial \tau_{yx}}{\partial y} + \frac{\partial \tau_{zx}}{\partial z} - \frac{\alpha E}{1-2\nu}\frac{\partial(u_a - u_w)}{\partial x} + X = 0$$

$$\frac{\partial \tau_{xy}}{\partial x} + \frac{\partial(\sigma_y - u_a)}{\partial y} + \frac{\partial \tau_{zy}}{\partial z} - \frac{\alpha E}{1-2\nu}\frac{\partial(u_a - u_w)}{\partial y} + Y = 0$$

$$\frac{\partial \tau_{xz}}{\partial x} + \frac{\partial \tau_{yz}}{\partial y} + \frac{\partial(\sigma_z - u_a)}{\partial z} - \frac{\alpha E}{1-2\nu}\frac{\partial(u_a - u_w)}{\partial y} + Z = 0$$

$$\frac{\partial}{\partial x}\left[k\frac{\partial u_w}{\partial x}\right] + \frac{\partial}{\partial y}\left[k\frac{\partial u_w}{\partial y}\right] + \frac{\partial}{\partial z}\left[k(\frac{\partial u_w}{\partial z} + 1)\right] = \frac{d\theta}{dt}$$

$$= \frac{d\theta_\sigma + d\theta_{u_a - u_w}}{dt} = m_1^w \frac{d(\sigma_m - u_a)}{dt} + m_2^w \frac{d(u_a - u_w)}{dt}$$

MATERIAL PARAMETERS NEEDED: E, ν, α, m_1^w, m_2^w and K

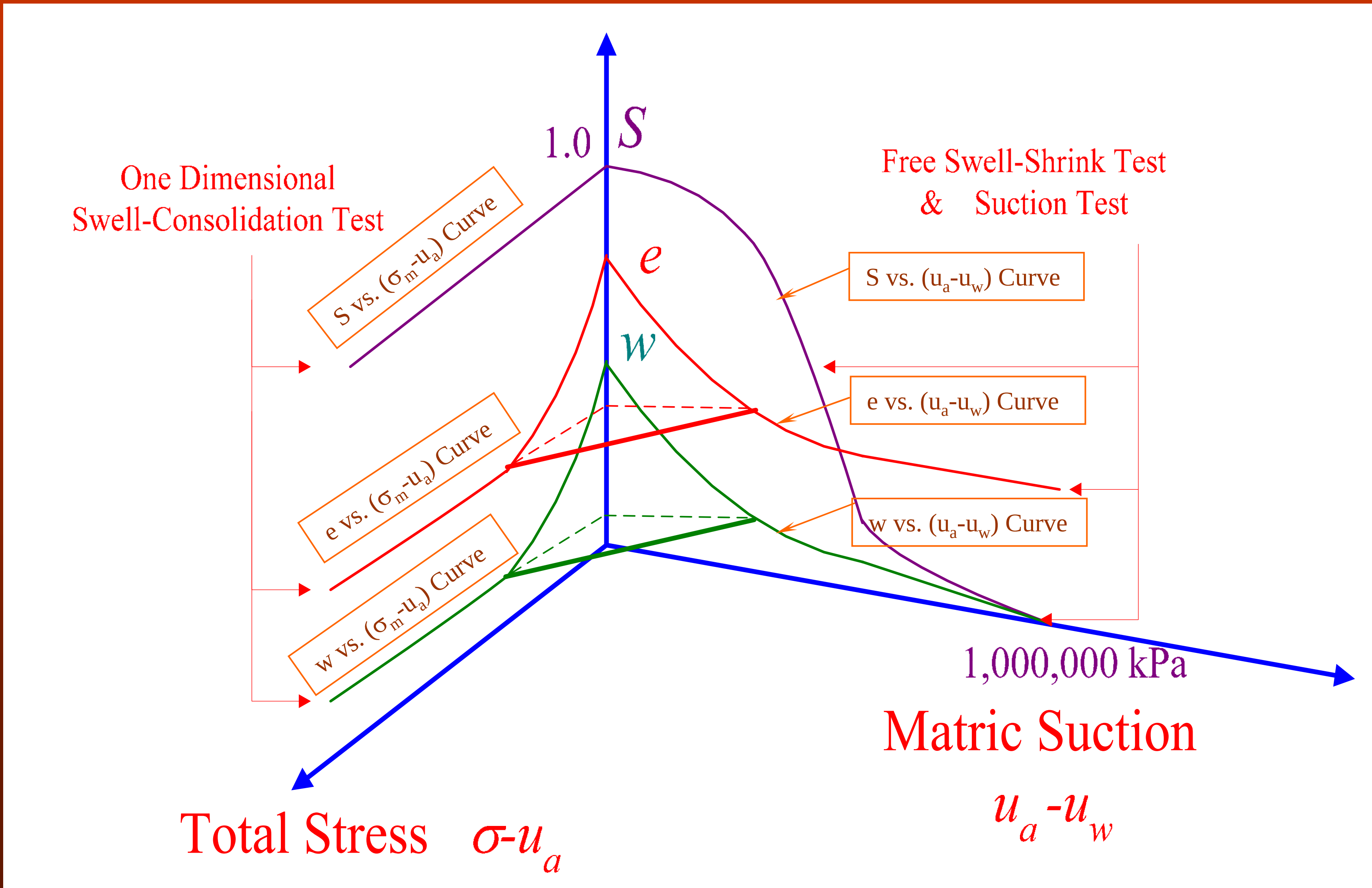
LABORATORY TESTS NEEDED (I)

METHOD PROPOSED BY XIONG ZHANG

- **ONE DIMENSIONAL CONSOLIDATION TEST**
- **FREE SWELL-SHRINK TEST**
- **SUCTION TESTS**

  (PRESSURE PLATE & SALT CONCENTRATION TESTS)
- **SPECIFIC GRAVITY TEST**

CONSTITUTE SURFACES OF UNSATURATED SOILS

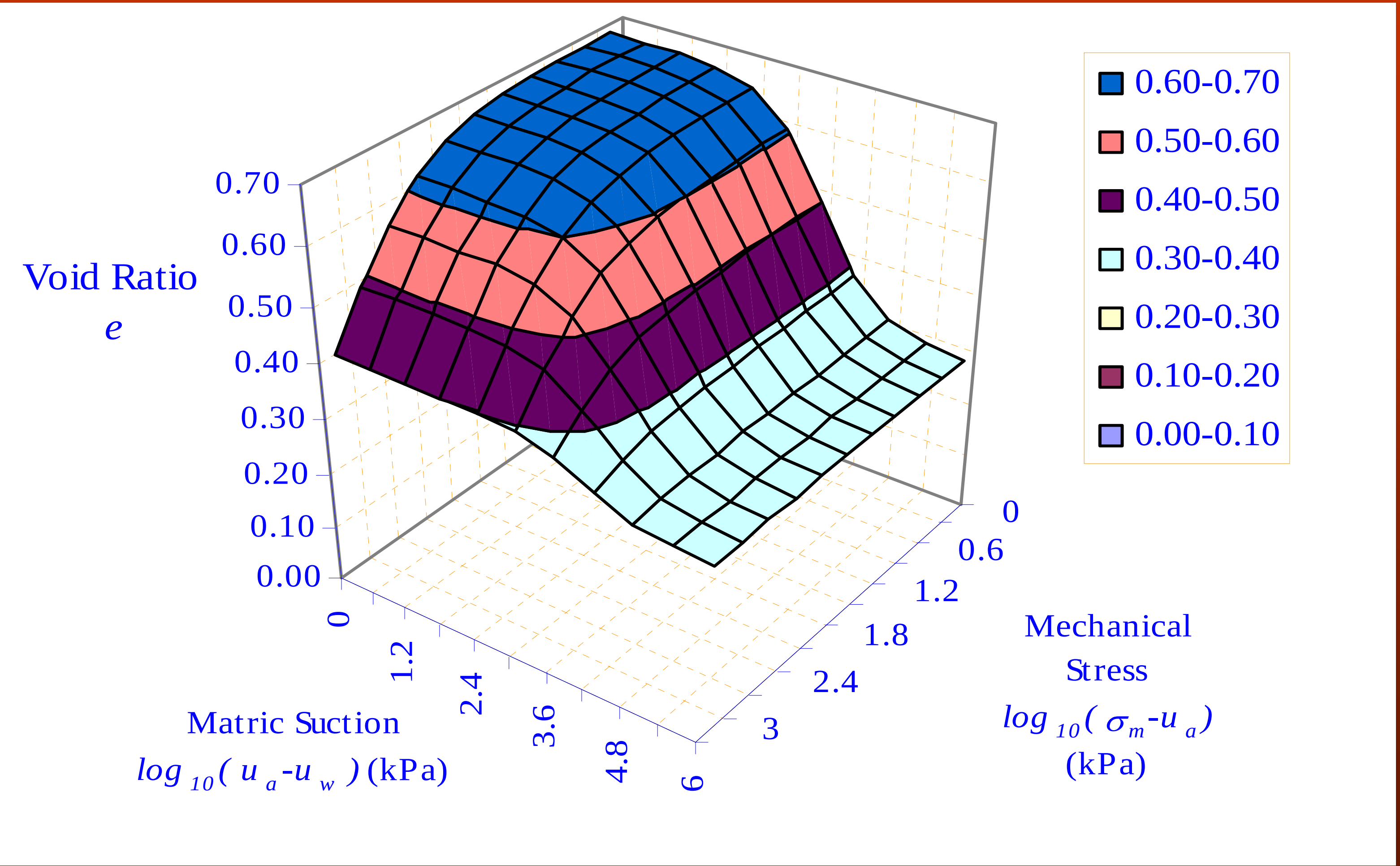


LABORATORY TESTS NEEDED (II)

METHOD PROPOSED BY PTI MANUAL

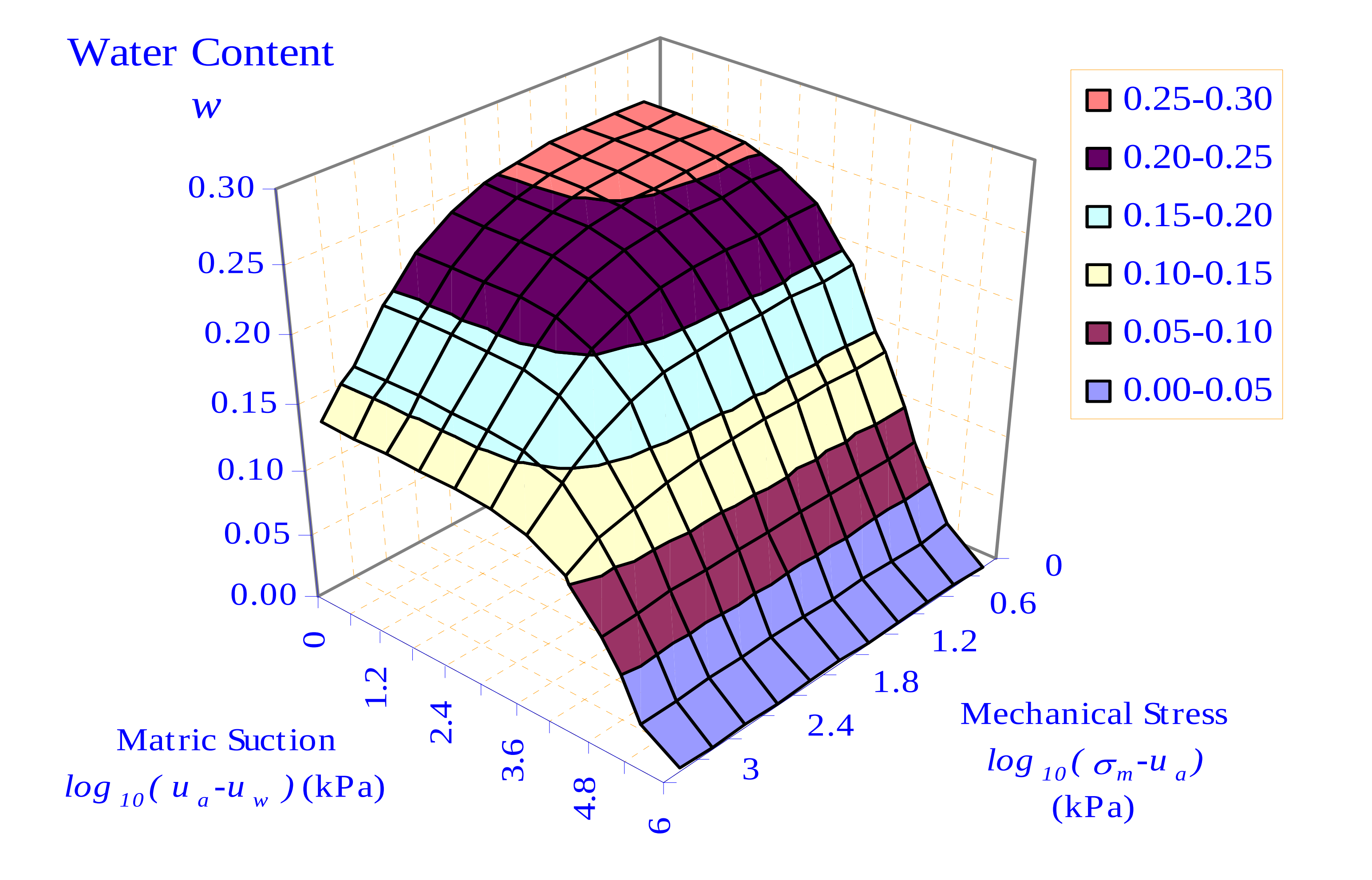
- **ATTERBERG LIMITS**
  - **LIQUID LIMIT**
  - **PLASTIC LIMIT**
- **HYDROMETER TEST**
  - **%-No.200**
  - **%-2 MICRONS**

VOID RATIO CONSTITUTIVE SURFACE OF A SOIL AT ARLINGTON, TEXAS



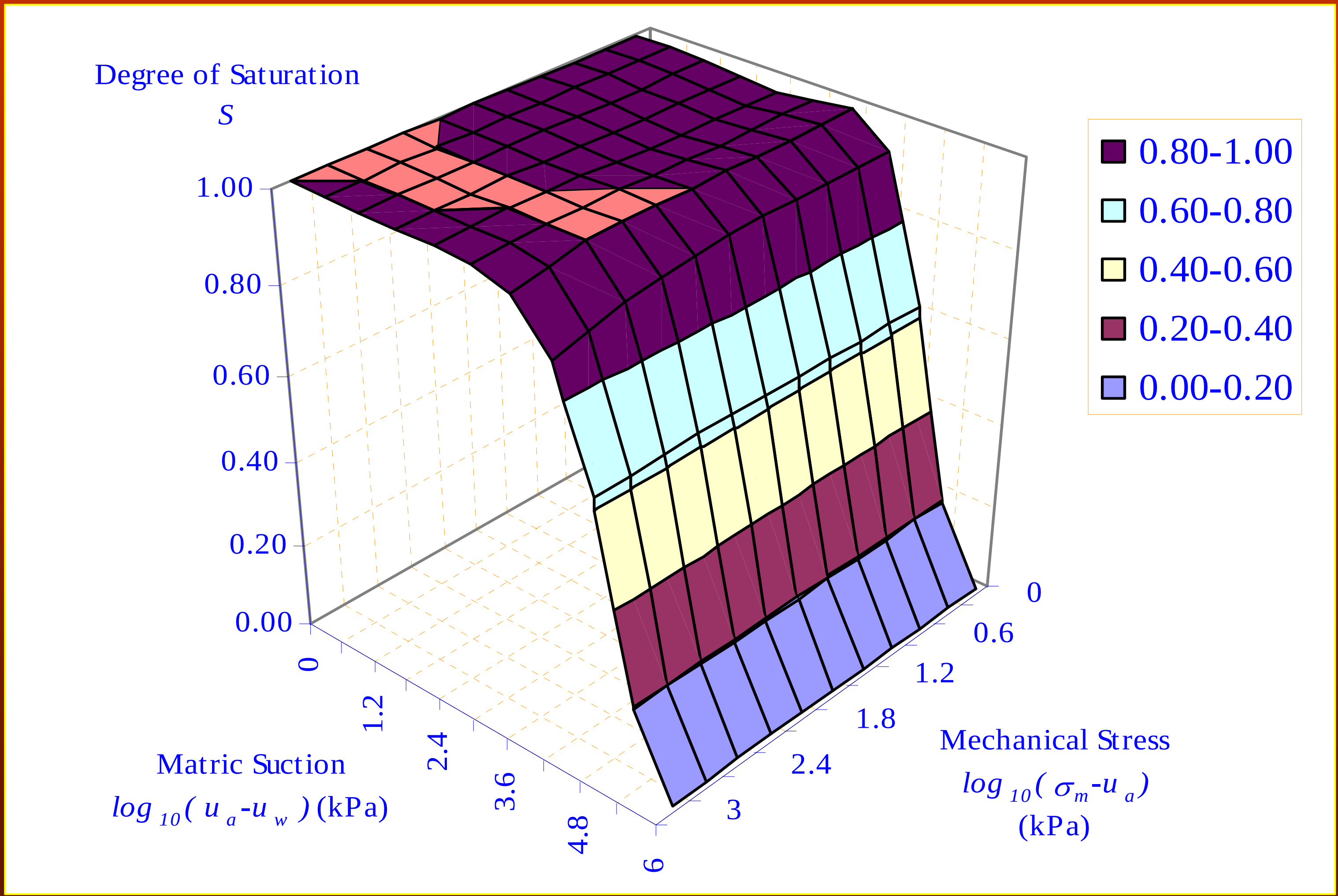
MATHMATICAL EXPRESSION: $$\frac{(\sigma_v - u_a)}{10^{\left(0.422\ln\left(\frac{0.492}{(e-0.195)}-1\right)+2.640\right)}} + \frac{(u_a - u_w)}{10^{\left(0.456\ln\left(\frac{0.387}{e-0.299}-1\right)+3.624\right)}} = 1$$

WATER CONTENT CONSTITUTIVE SURFACE OF A SOIL AT ARLINGTON, TEXAS

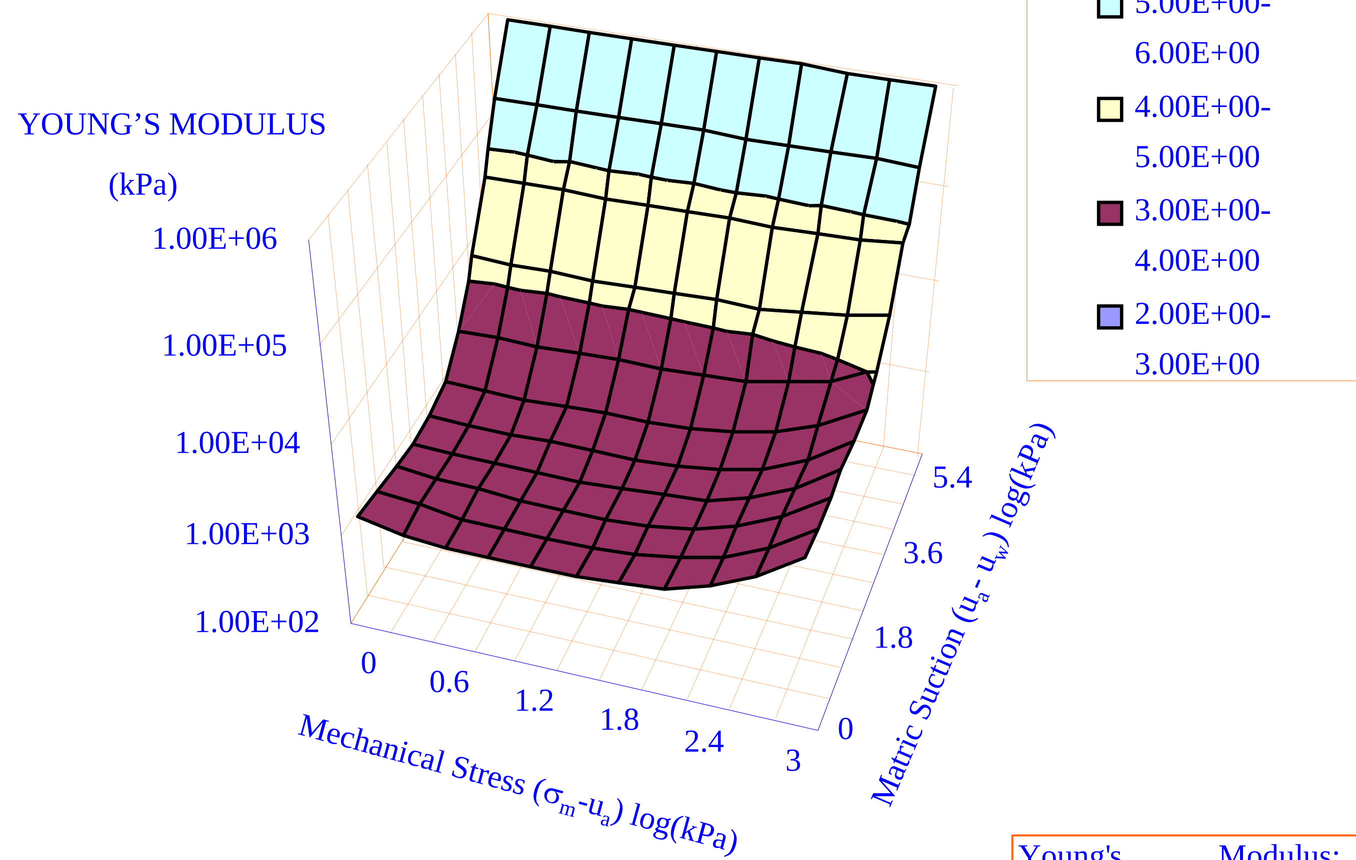


MATHEMATICAL EXPRESSION: $$\frac{\sigma_v - u_a}{10^{\left(0.422\ln\left(\frac{0.186}{(w-0.0737)}-1\right)+2.640\right)}} + \frac{u_a - u_w}{10^{\left(0.672\ln\left(\frac{0.286}{(w+0.0263)}-1\right)+4.386\right)}} = 1$$

DEGREE OF SATURATION CONSTITUTIVE SURFACE OF A SOIL AT ARLINGTON, TEXAS



MATERIAL PARAMETERS (I)
YOUNG'S MODULUS SURFACE *

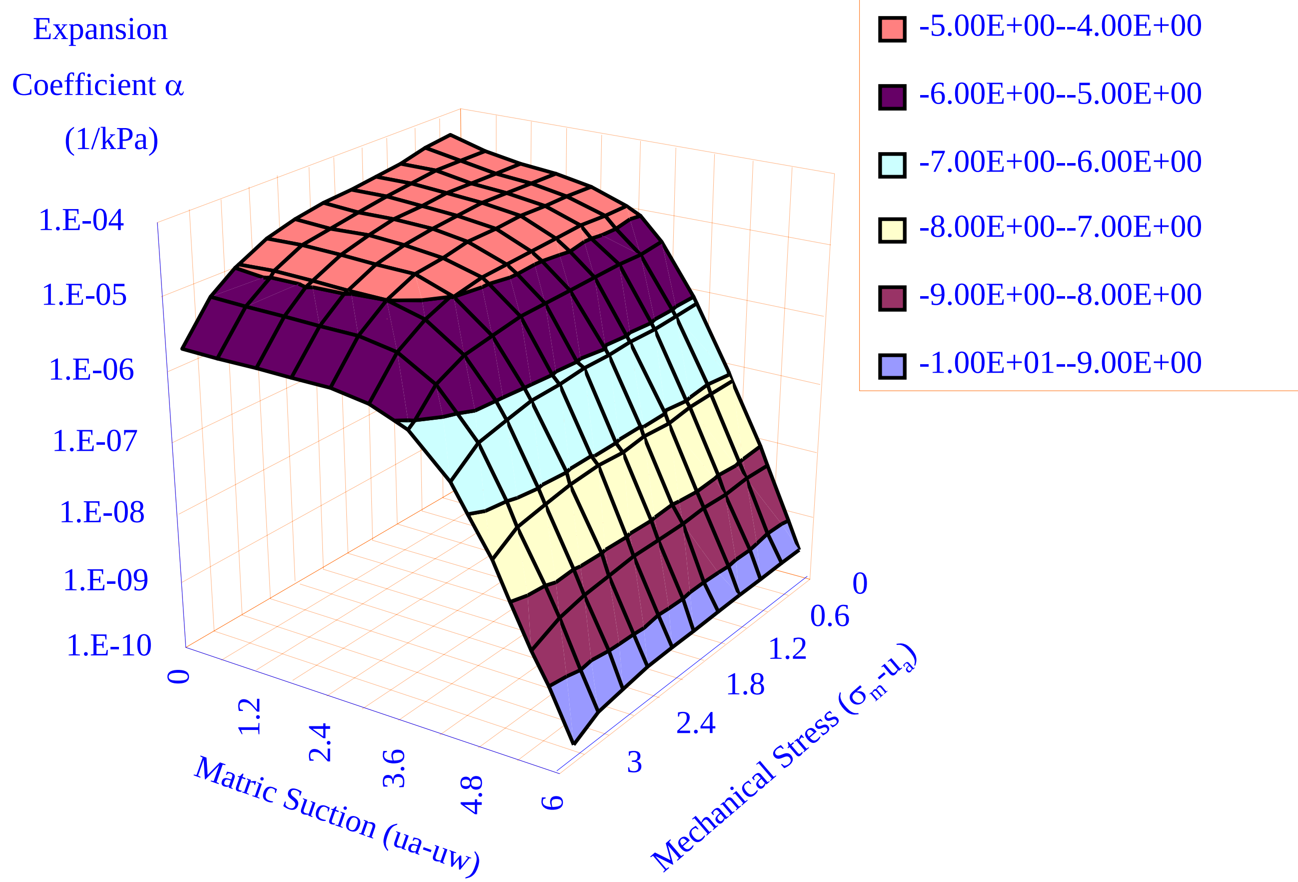


Young's Modulus:

$$E = \frac{3(1-2\mu)}{m_1^s}$$

*** RELATED TO THE MEAN PRINCIPAL STRESS COMPRESSION INDEX γ_σ IN THE PTI MANUAL**

MATERIAL PARAMETERS (II)
COEFFICIENT OF EXPANSION SURFACE *

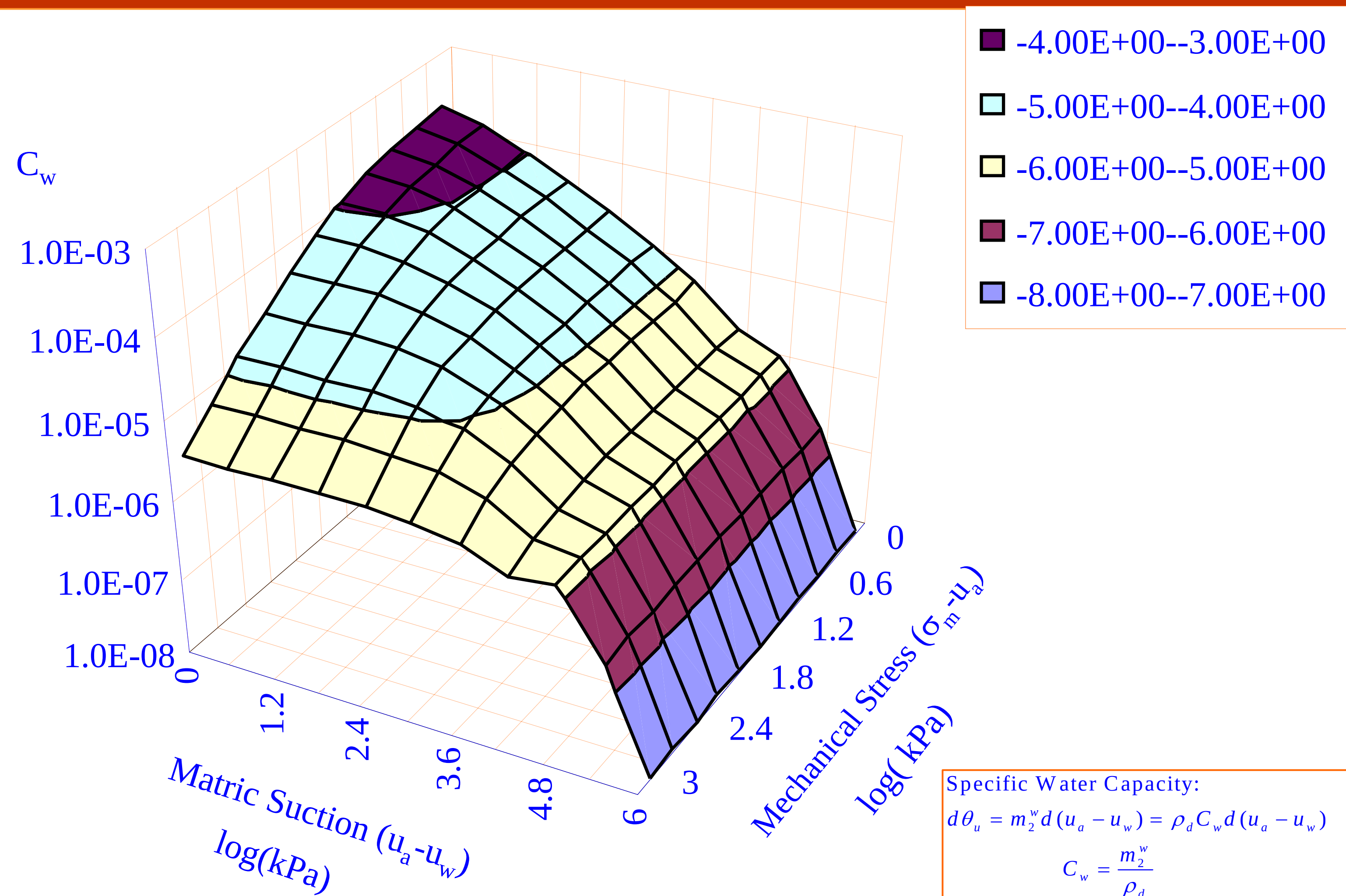


Coefficient of Expansion:

$$\alpha = \frac{m_2^s}{3}$$

* **RELATED TO THE SUCTION COMPRESSION INDEX γ_h IN THE PTI MANUAL**

MATERIAL PARAMETERS (III)
SPECIFIC WATER CAPACITY SURFACE *



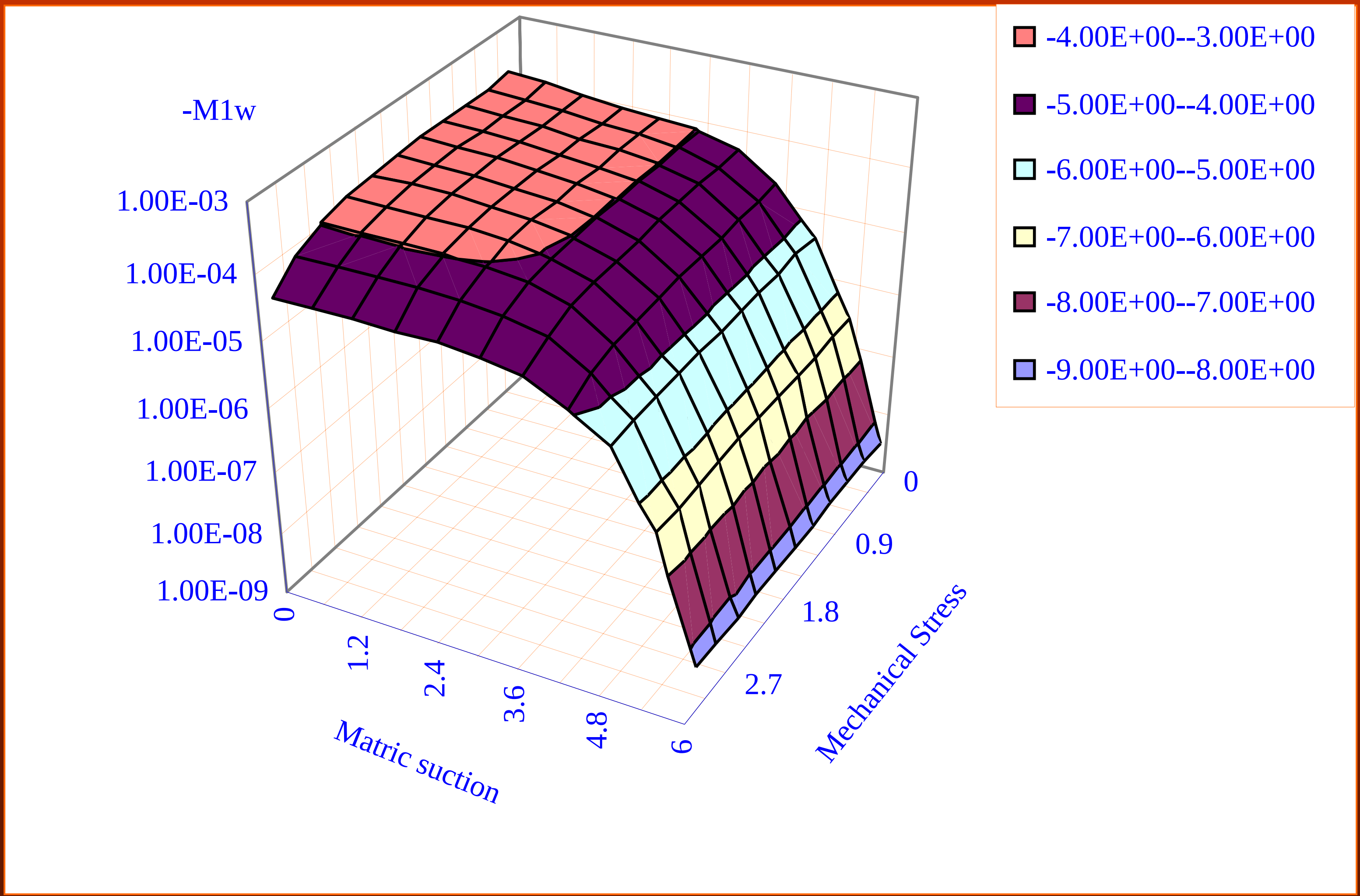
Specific Water Capacity:

$$d\theta_u = m_2^w d(u_a - u_w) = \rho_d C_w d(u_a - u_w)$$

$$C_w = \frac{m_2^w}{\rho_d}$$

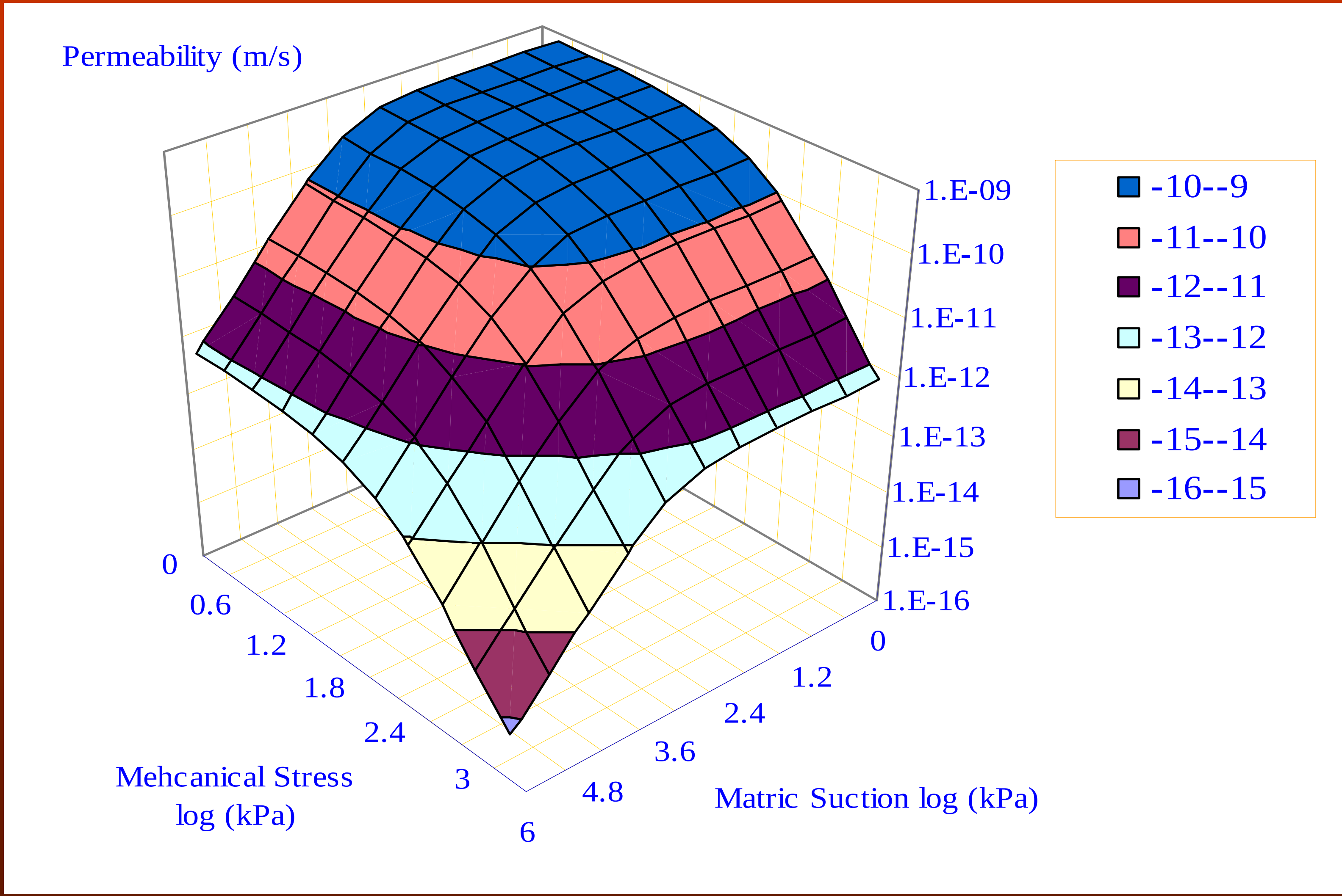
* RELATED TO *S* VALUE IN THE PTI MANUAL

MATERIAL PARAMETERS (IV)
WATER GENERATION PARAMETER SURFACE*



*** THE ABILITY OF THE MEAN MECHANICAL STRESS TO SQUEEZE WATER OF THE SOIL**

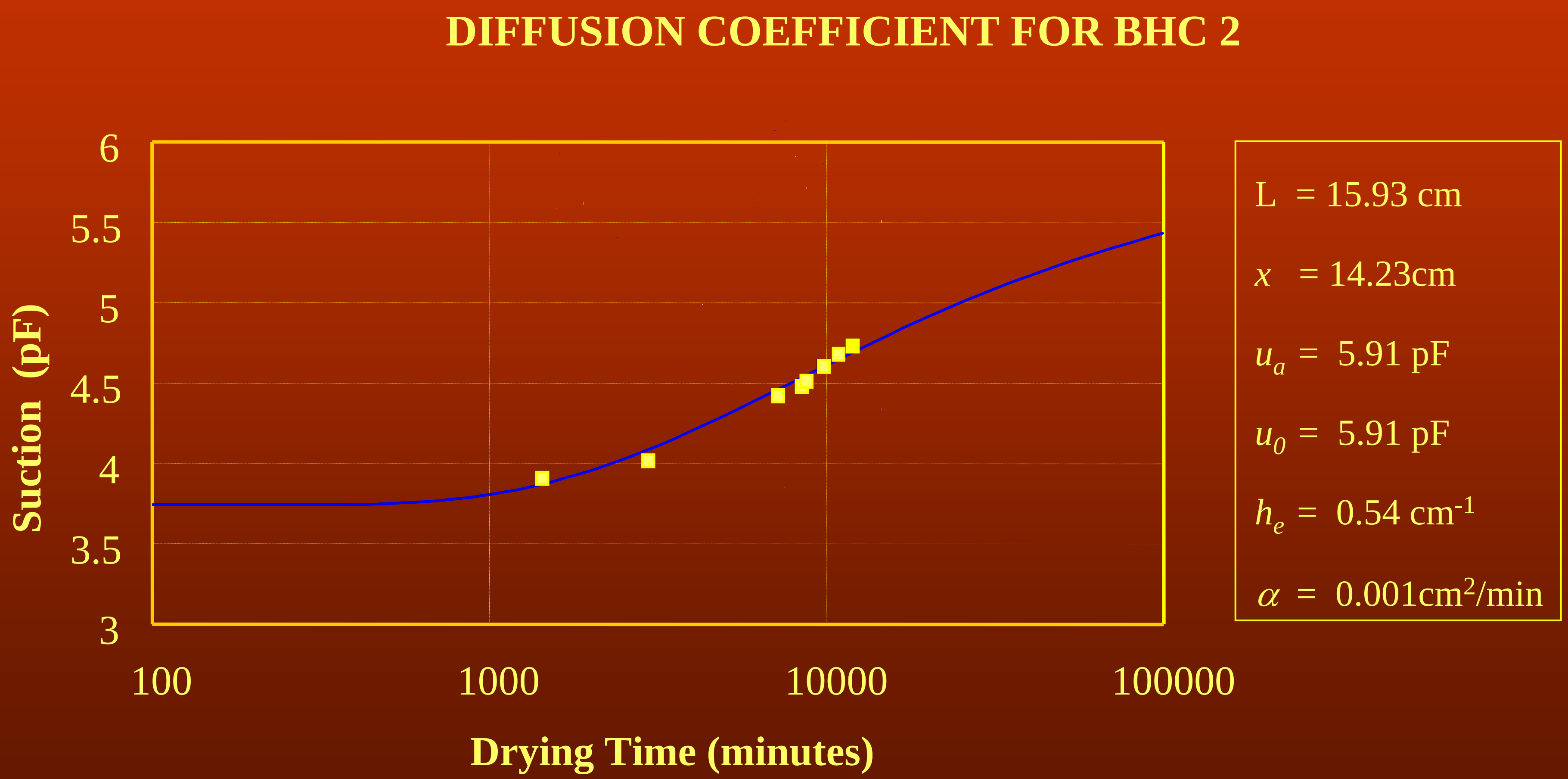
MATERIAL PARAMETERS (V)
COEFFICIENT OF PERMEABILITY SURFACE*



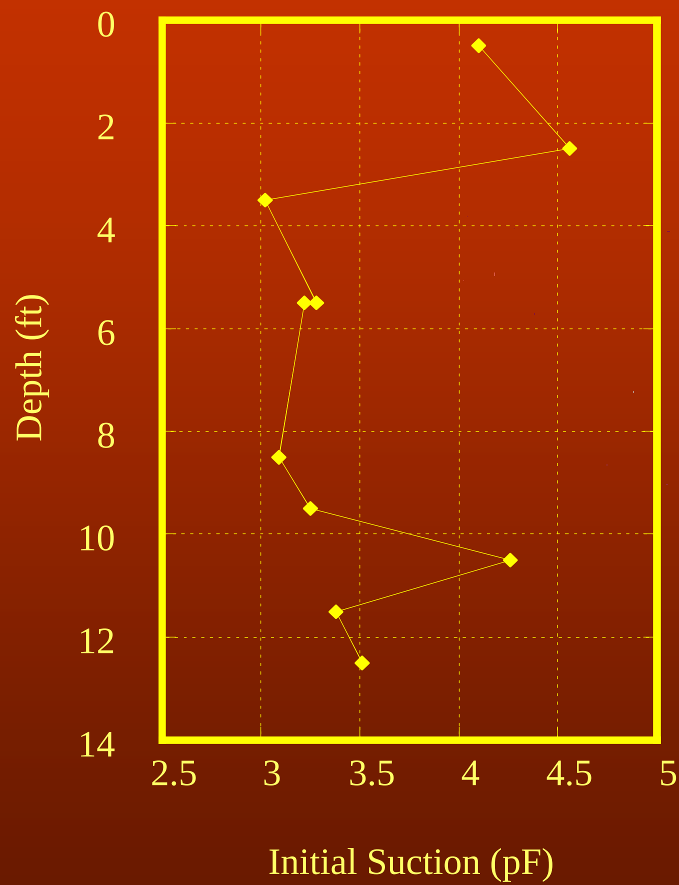
*** RELATED TO THE DIFFUSION COEFFICIENT α IN THE PTI MANUAL**

MEASURING DIFFUSION COEFFICIENT SAMPLE PARAPRATION & EQUIPMENT SETUP

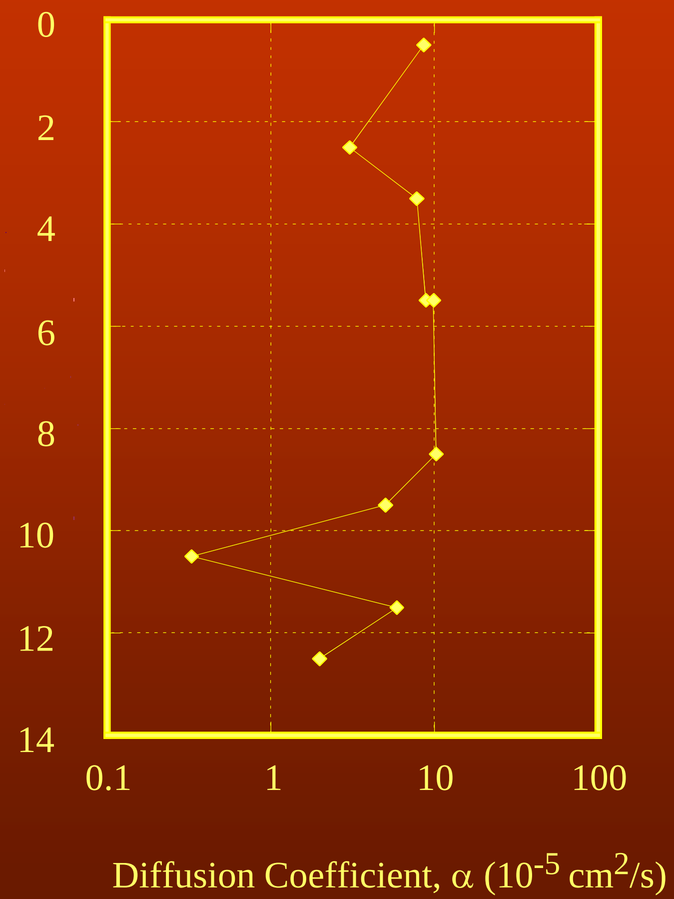
BACKCALCULATING DIFFUSION COEFFICIENT



MATERIAL PARAMETERS (VI)
DETERMINATION OF DIFFUSION COEFFICIENT



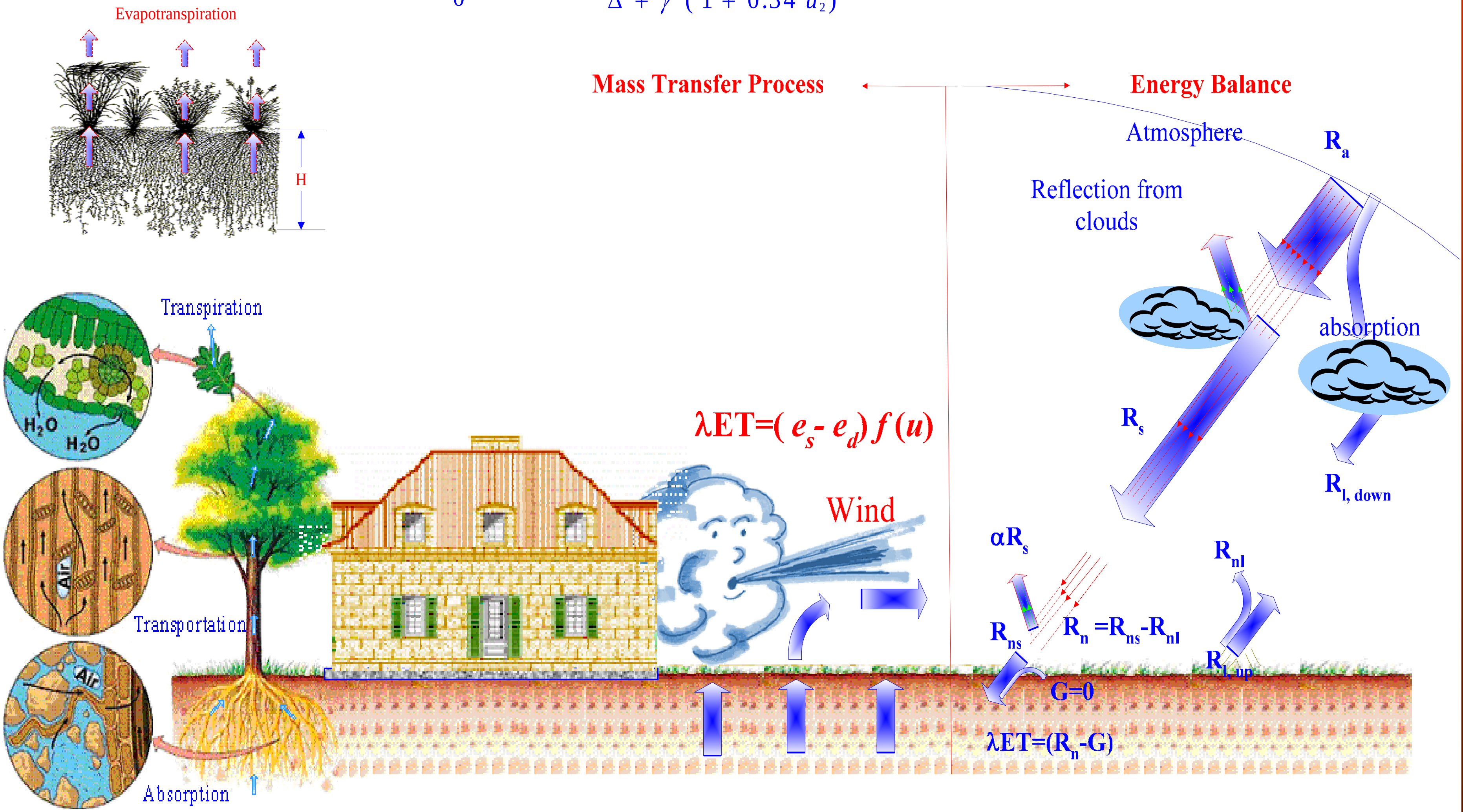
SUCTION PROFILE
(Fort Worth IH 820)



MEASURED DIFFUSION COEFFICIENT

FACTORS INFLUENCING EVAPOTRANSPIRATION

$$ET_0 = \frac{0.408\,\Delta\,(R_n - G) + \gamma\,\frac{900}{T+273}\,u_2\,(e_s - e_a)}{\Delta + \gamma\,(1 + 0.34\,u_2)}$$



EVAPOTRANSPIRATION PROCESS

- TWO PROCESSES

  1. VAPORIZATION OF WATER
  2. VAPOR REMOVAL

- SEVEN INFLUENCING FACTORS

  1. SOLAR RADIATION
  2. RELATIVE HUMIDITY
  3. WIND SPEED
  4. RAINFALL
  5. VEGETATION TYPES
  6. SOIL PERMEABILITY
  7. SOIL WATER CONTENT

ESTIMATION OF EVAPOTRANSPIRATION

- **CURRENTAVAILABLE METHODS**

  1).THE TEMPERATURE METHODS

  (THORNTHWAITE, MCCLOUD, MBC)

  2).THE RADIATION METHODS

  (MMBC, HARG, TURC)

  3).THE COMBINATION METHODS

  (FAO 56 PM, ASCE2000 PM)

- **THE FAO 56 PENMAN-MONTEITH METHOD**

  1). AN INTERNATIONAL STANDARD, GLOBALLY VALID

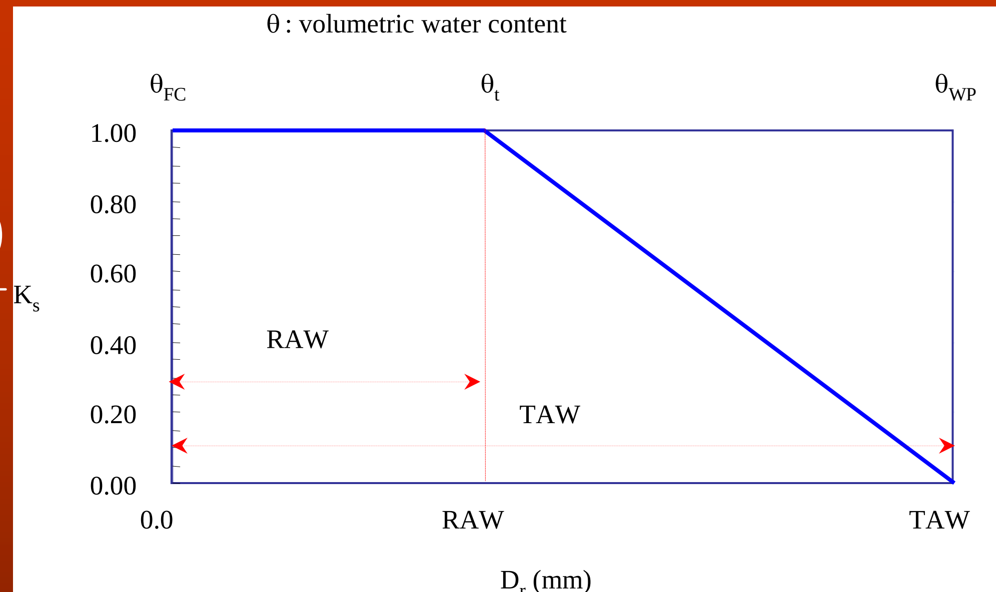
  2). CAN USE DAILY OR HOURLY WEATHER DATA

  3). METHOD FOR ESTIMATING MISSING DATA AVAILABLE

POTENTIAL VS. ACTUAL EVAPOTRANSPIRATION

The FAO 56 Penman-Montieth Method

$$ET_0 = \frac{0.408\Delta\left(R_n - G\right) + \gamma \frac{900}{T+273} u_2 \left(e_s - e_a\right)}{\Delta + \gamma\left(1 + 0.34 u_2\right)}$$



$ETc = Kc\ ET_0$

ETc adjusted = Ks $\times$ Kc $\times$ ET_0

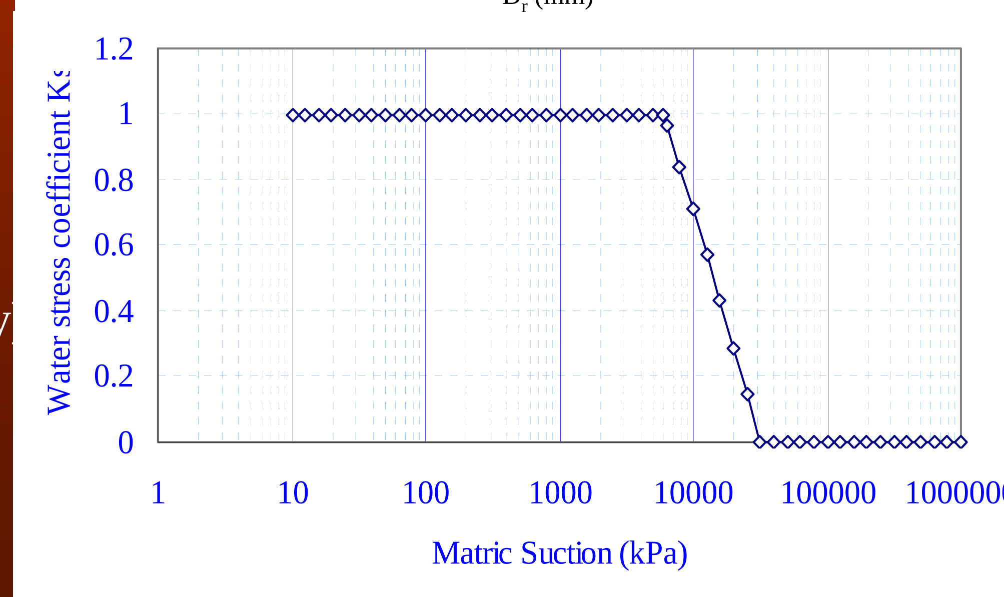
ET_0 =reference evapotranspiration (mm/day)

ETc=crop evapotranspiration (mm/day)

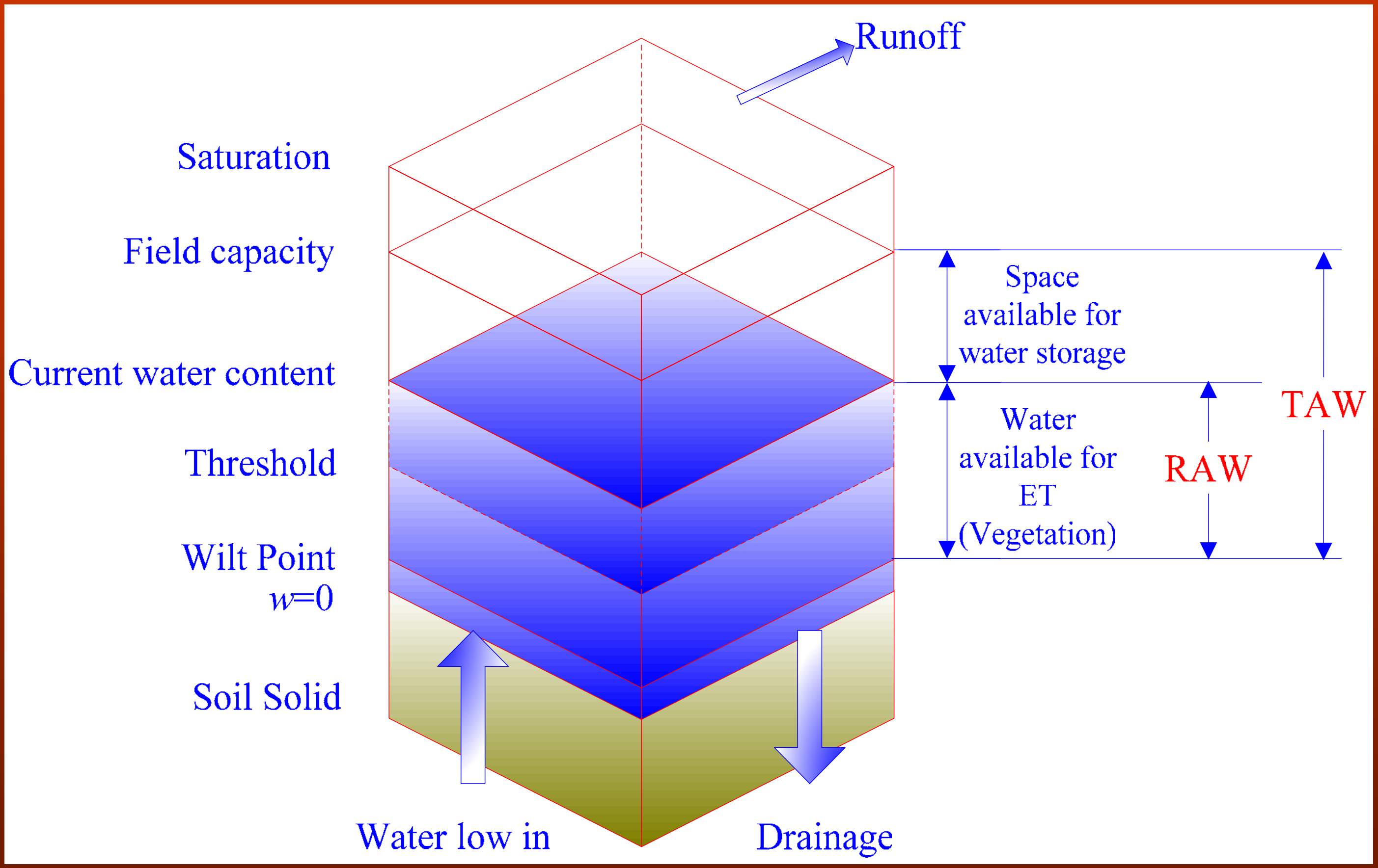
(ETc)adj=actual evapotranspiration (mm/day)

Kc=crop coefficient (dimensionless)

Ks=water stress coefficient(dimensionless)



SOIL WATER BALANCE



TAW=the total available soil water in the root zone (mm)

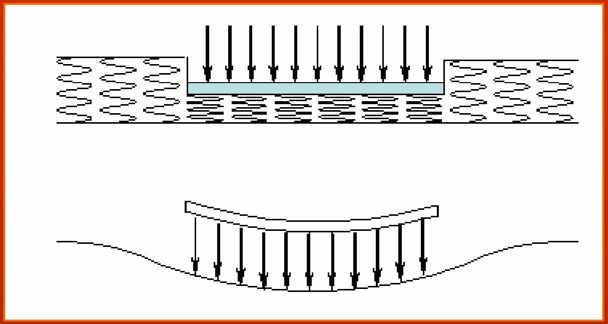
RAW= the readily available soil water in the root zone (mm)

FOUNDATION MODELS (I)

- **WINKLER FOUNDATION MODEL**

  ASSUMPTION: THE FOUNDATION IS CONSIDERED AS A NUMBER OF CLOSELY SPACED, VERTICAL, INDEPENDENT, LINEAR ELASTIC SPRINGS PROVIDING VERTICAL REACTION ONLY.

  DRAWBACK: SHEAR DEFORMATION CAN NOT BE SIMULATED.



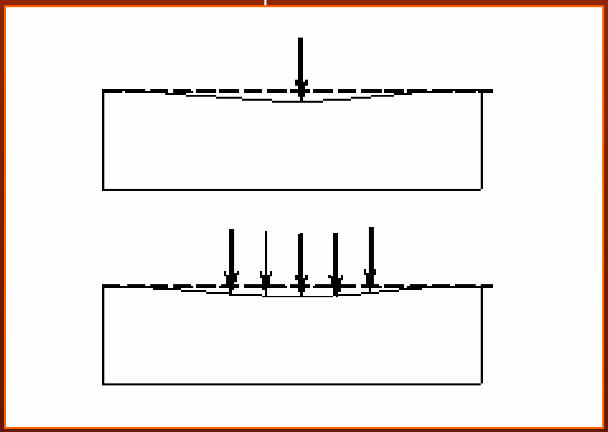
WINKLER FOUNDATION

ELASTIC HALF SPACE FOUNDATION

ASSUMPTION: THE SOIL IS CONSIDERED AS AN ELASTIC, ISOTROPIC, AND HOMOGENEOUS SEMI-INFINITE CONTINUUM WITH E AND *v*

DRAWBACKS: (1). SEPARATION AND FRICTION BETWEEN THE SLAB AND THE FOUNDATION ARE NOT EASY TO SIMULATE.

(2) NOT EASY TO DETERMINE E AND *v* FOR MULTILAYERS



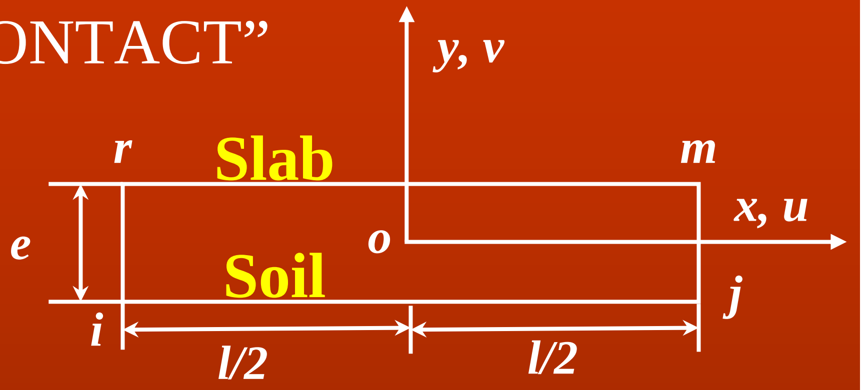
ELASTIC HALF SPACE

SOIL STRUCTURE INTERACTION (II)-CONTACT ELEMENT

1. NORMAL BEHAVIOR : "HARD CONTACT"

P=0 for h>0 (OPEN),AND

h=0 for P>0 (CLOSED)



2. TANGENTIAL BEHAVIOR: COULOMB FRICTION MODEL

THE EQUIVALENT FRICTIONAL STRESS

$$\tau_{eq}=(\tau_x^2+\tau_y^2)^{1/2}$$

THE CRITICAL STRESS *

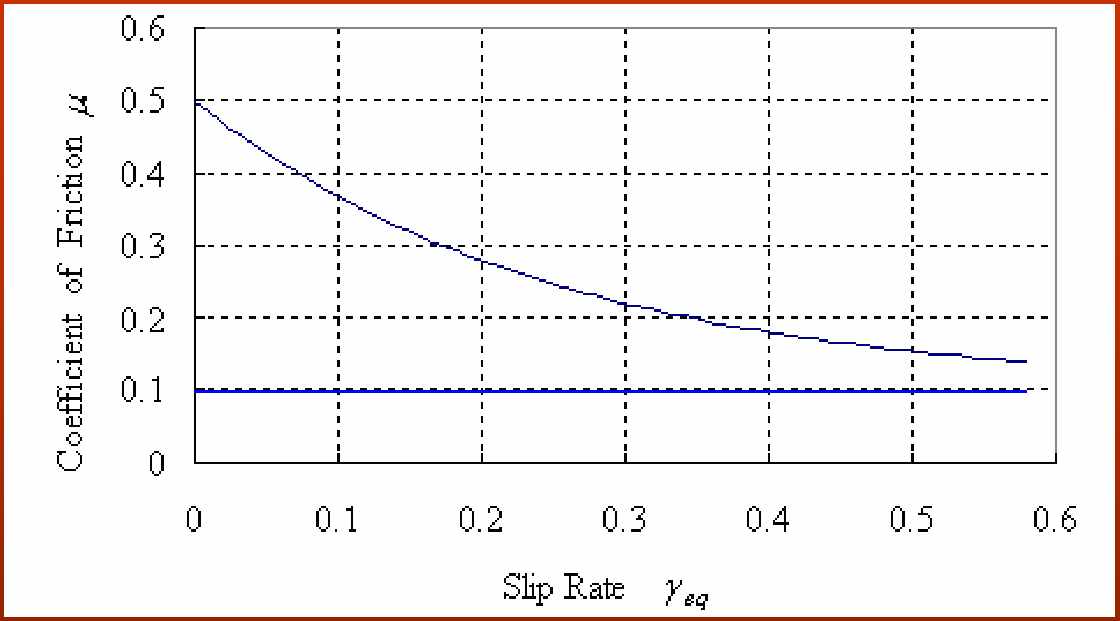
$$\tau_{critical}=\mu P$$

WHERE, P=CONTACT PRESSURE

IF $\tau_{eq} \leq \tau_{critical}$, NO RELATIVE MOTION

* ALTERNATIVELY, $\tau_{critical}=(\sigma-u_a)\mathrm{tg}\phi'+(u_a-u_w)\mathrm{tg}\phi''+C$

FRICTION COEFFICIENTS AFTER SLIPPING



IF $\tau_{eq} > \tau_{critical}$, THEN

$$\mu = \mu_k - (\mu_s - \mu_k) e^{-d_c \dot{\gamma}_{eq}} = 0.1 + 0.4 e^{-4\dot{\gamma}_{eq}}$$

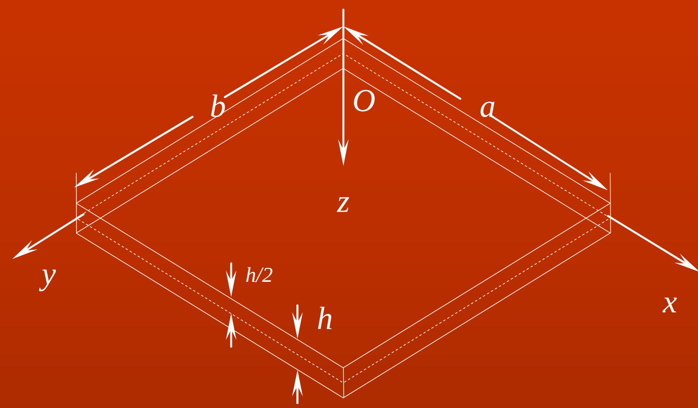
μ_k =the kinetic friction coefficient

μ_s =the static friction coefficient

d_c =a user-defined decay coefficient, and

$\dot{\gamma}_{eq}$ = the slip rate (see Oden, J. T. and J. A. C. Martins, 1985).

KIRCHHOFF PLATE THEORY (PURE BENDING)

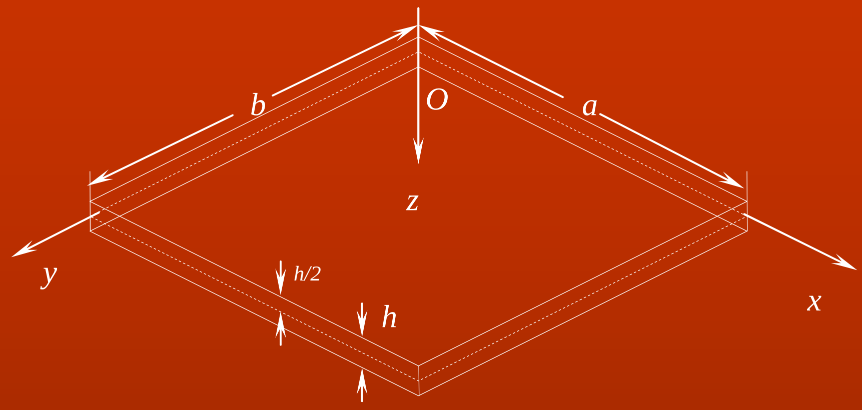


- STRAIGHT LINES PERPENDICULAR TO THE MID-SURFACE BEFORE DEFORMATION, REMAIN STRAIGHT AFTER DEFORMATION.
- THE TRANSVERSE NORMALS DO NOT EXPERIENCE ELONGATION.
- THE TRANSVERSE NORMALS ROTATE SUCH THAT THEY REMAIN PERPENDICULAR TO THE MID-SURFACE AFTER DEFORMATION.

$$\varepsilon_z = \frac{\partial w}{\partial z} = 0, \gamma_{yz} = \frac{\partial w}{\partial y} + \frac{\partial v}{\partial z} = 0, \varepsilon_z = \frac{\partial u}{\partial z} + \frac{\partial w}{\partial x} = 0$$

$$u_{z=0} = 0, v_{z=0} = 0, w_{z=0} = w(x, y)$$

MINDLIN PLATE THEORY



- STRAIGHT LINES PERPENDICULAR TO THE MID-SURFACE BEFORE DEFORMATION, REMAIN STRAIGHT AFTER DEFORMATION.

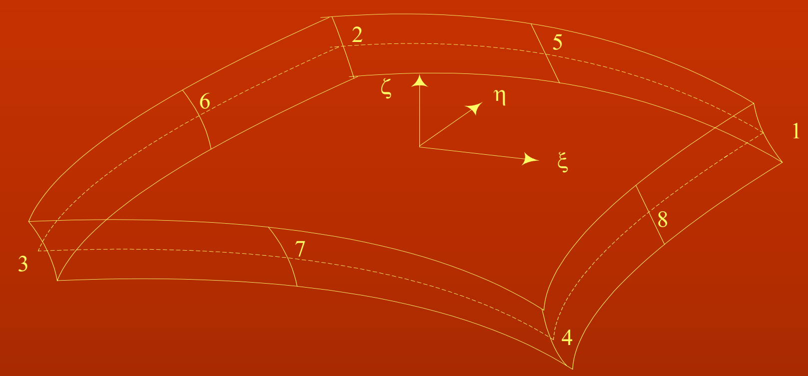
$$\varepsilon_z = \frac{\partial w}{\partial z} = 0, \gamma_{yz} = \frac{\partial w}{\partial y} + \frac{\partial v}{\partial z} \neq 0, \gamma_{xz} = \frac{\partial u}{\partial z} + \frac{\partial w}{\partial x} \neq 0$$

- THE TRANSVERSE NORMALS DO NOT EXPERIENCE ELONGATION.

$$u_{z=0} = 0, v_{z=0} = 0, w_{z=0} = w(x, y)$$

- THE TRANSVERSE NORMALS ROTATE SUCH THAT THEY REMAIN PERPENDICULAR TO THE MID-SURFACE AFTER DEFORMATION.

GENERAL SHELL ELEMENT



- THE TRANSVERSE NORMALS REMAIN STRAIGHT AFTER DEFORMATION AND THE LENGTH REMAIN UNCHANGED.

- ADVANTAGES:

1. 5 DEGREES OF FREEDOM, CAN SIMULATE PLATE BENDING WITH SHEAR DEFORMATION AND PLATE STRETCHING
2. NEGLECT THE STRAIN ENERGY CAUSED BY σ_{Z}, MORE ACCURATE.
3. THE MID-SURFACE CAN BE ARBITRARY
4. SHEAR LOCKING CAN BE SOLVED TO ANALYZE THIN SHELL.

SOIL-STRUCTURE MOISTURE VARIATION SIMULATIONS

Concrete:

$\alpha = 0$

$\varepsilon_v = \varepsilon_\sigma + \varepsilon_T = Bd\sigma + 3\alpha dT$

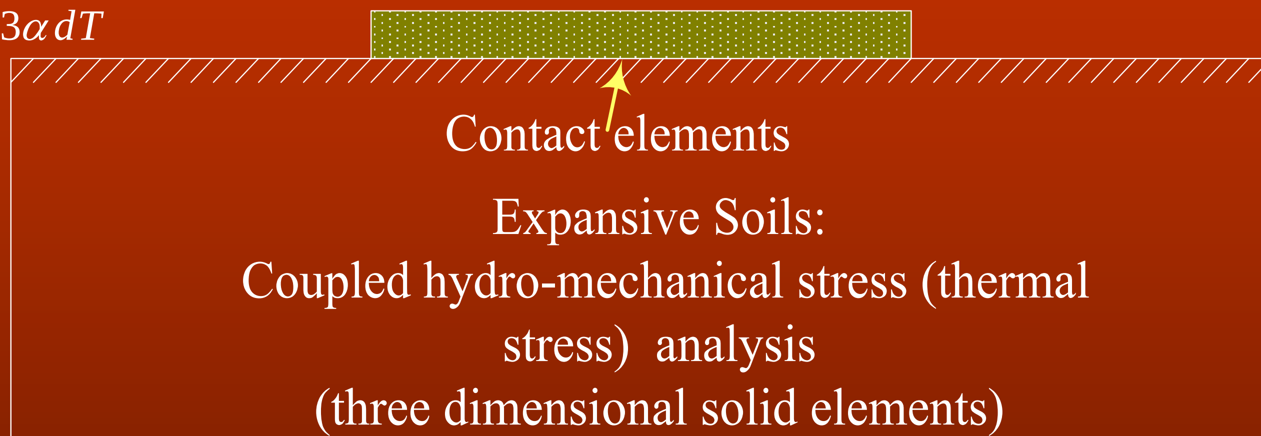
$= Bd\sigma$

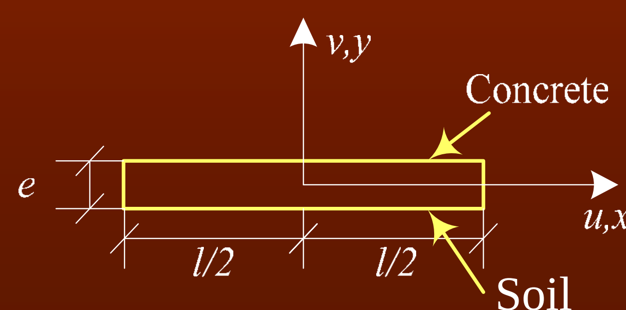
Contact Element :

$k = 0$

$q = k\left(T_A - T_B\right) = 0$

Concrete:
mechnaical stress analysis
(shell elements)





BOUNDARY CONDITIONS

FLUX BOUNDARY CONDITION:

AD and BC: $q_x = 0$

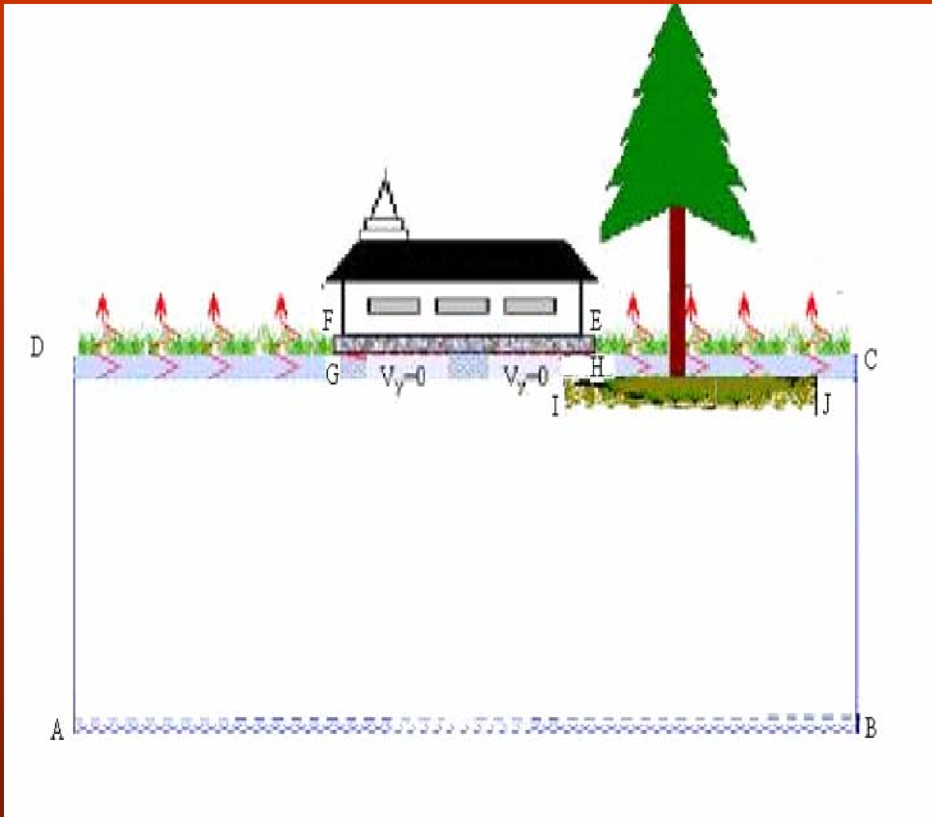
AB: $u_a - u_w = 10kPa$

DG and CH: $q_y = ETP - Rainfall$ (Bare soil) or

$S = (ETP - Rainfall)/d_{grass}$ (Grass) or

$S = ETP/d_{tree}$ (Tree)

GH: $q_y = 0$ *



Typical Environment around a House

MECHANICAL BOUNDARY CONDITION:

AD and BC: $u = 0$

AB : $u = v = 0$

DG and CH: None

GH : (Contact element)

* It is realized by thermal behavior of contact element

MATERIAL PROPERTIES FOR STRUCTURE

Mechanical Behavior:

Linearly elastic concrete

Thermal Behavior:

No Expansion

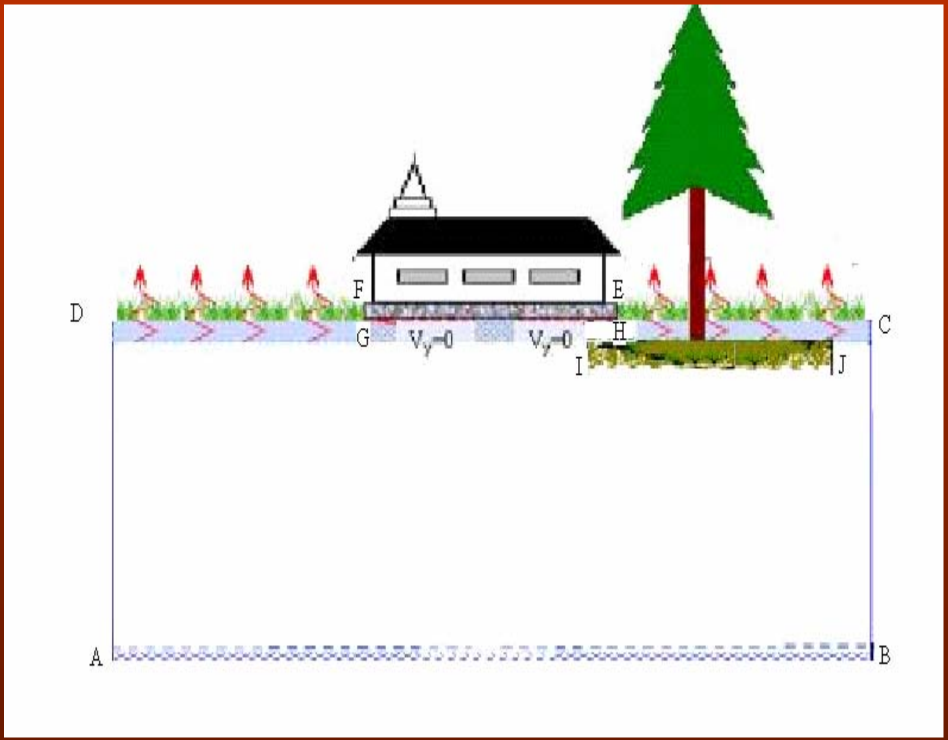
No Heat Generation

Boundary Condition:

Zero Initial Condition

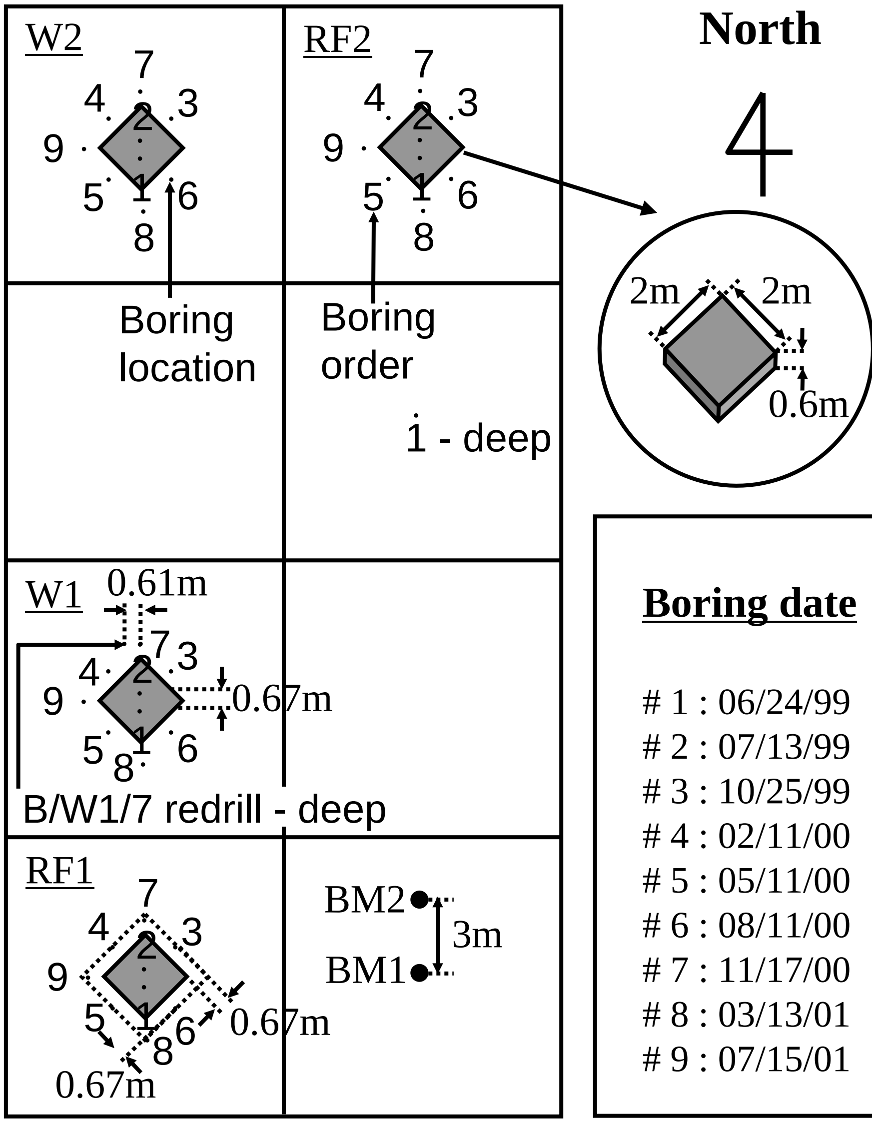
Load:

Gravity



VERIFICATION-PLAN VIEW OF THE SITE

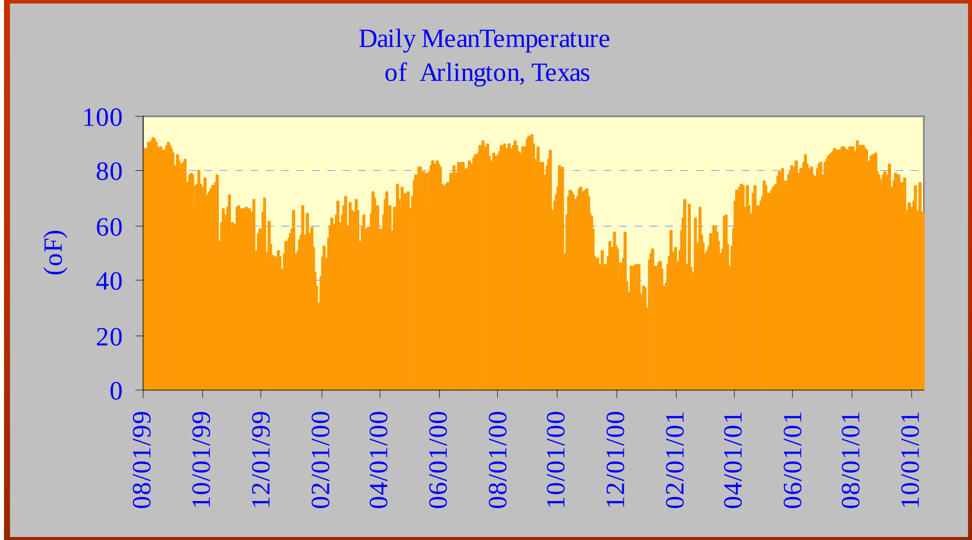
Site in Arlington, Texas

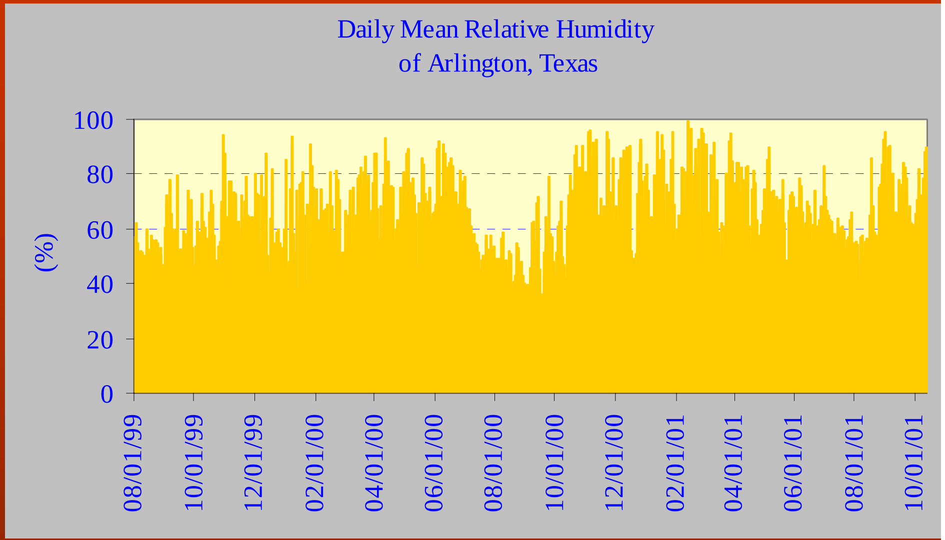


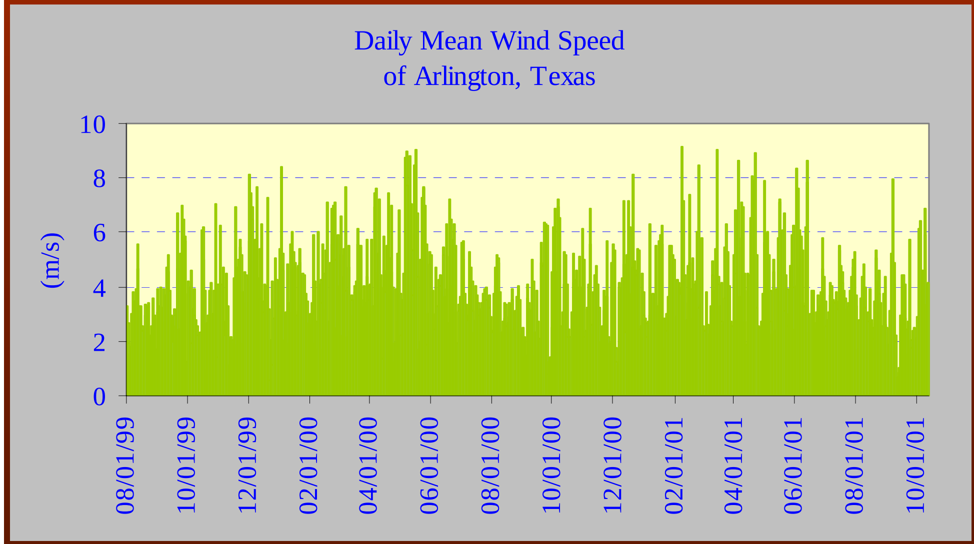
Boring date

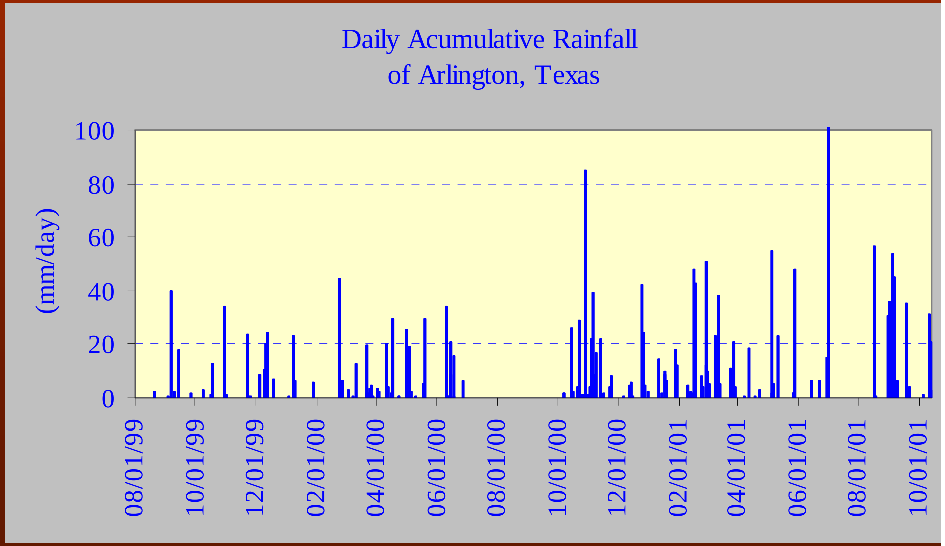
1 : 06/24/99
2 : 07/13/99
3 : 10/25/99
4 : 02/11/00
5 : 05/11/00
6 : 08/11/00
7 : 11/17/00
8 : 03/13/01
9 : 07/15/01

ENVIRONMENTAL FACTORS AT ARLINGTON

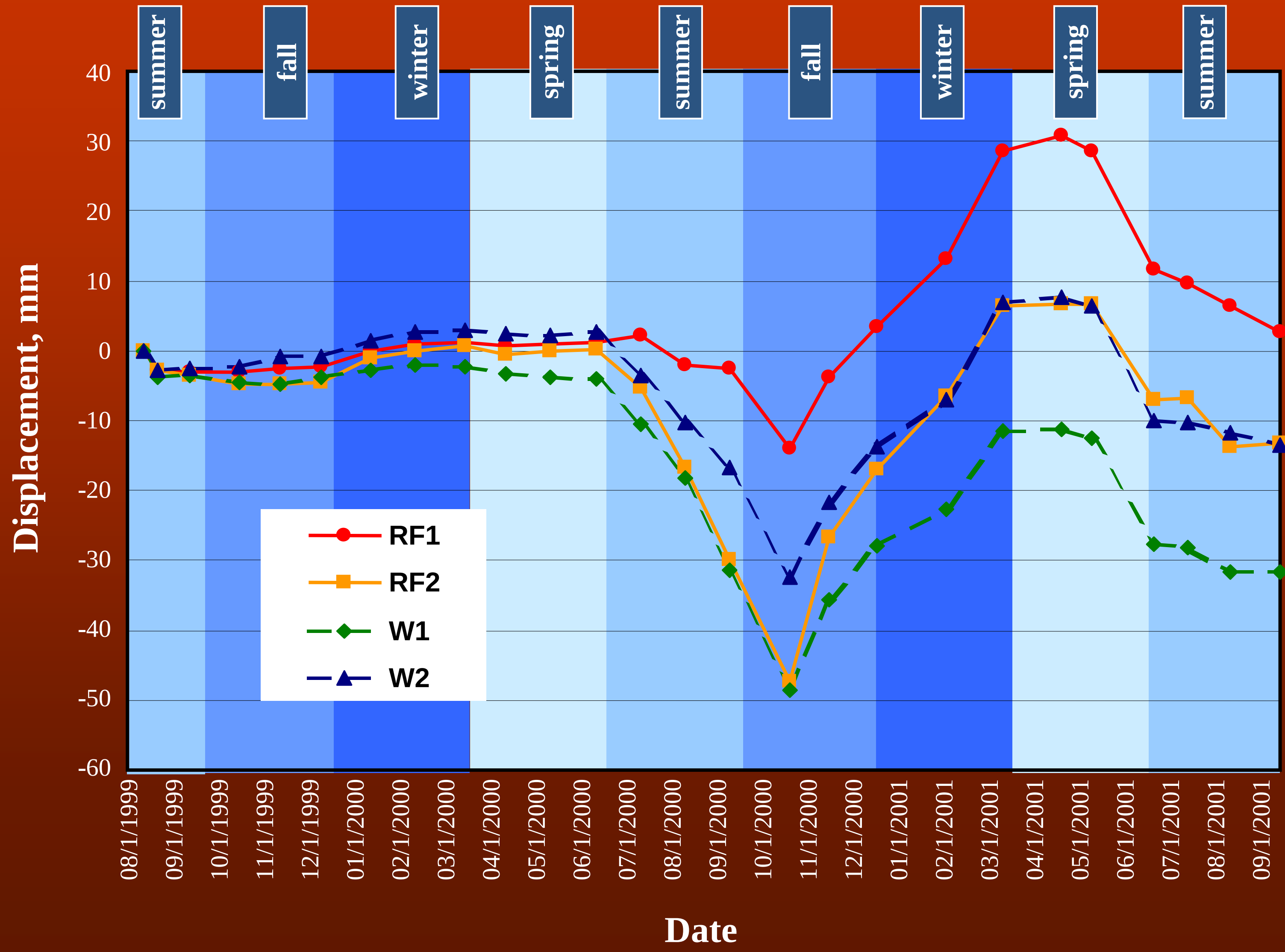




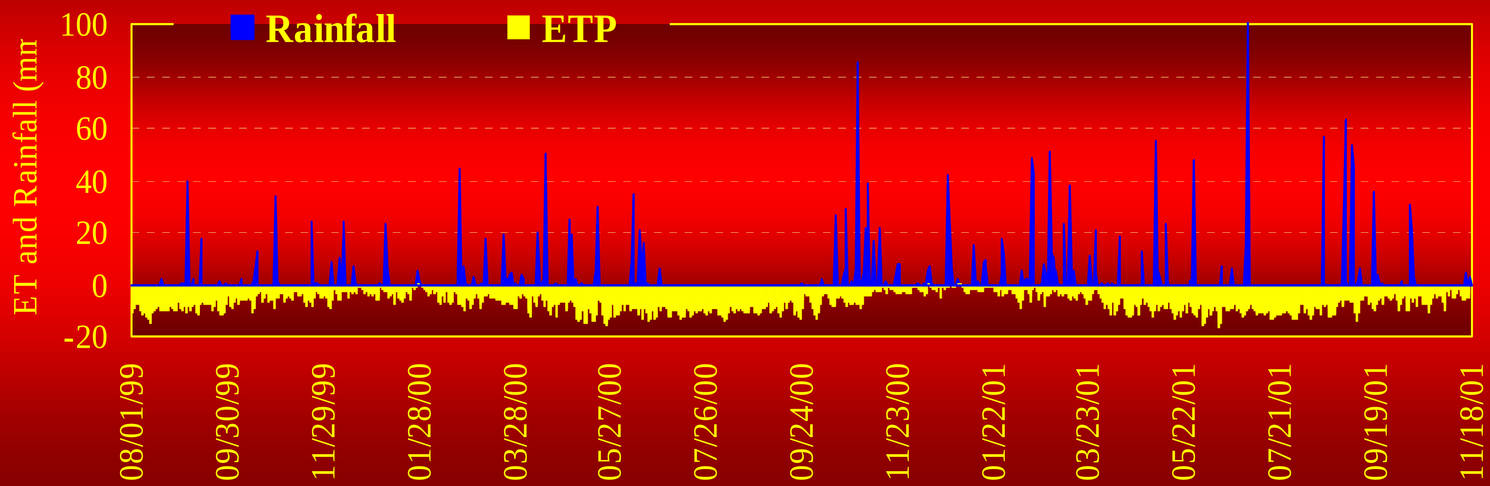




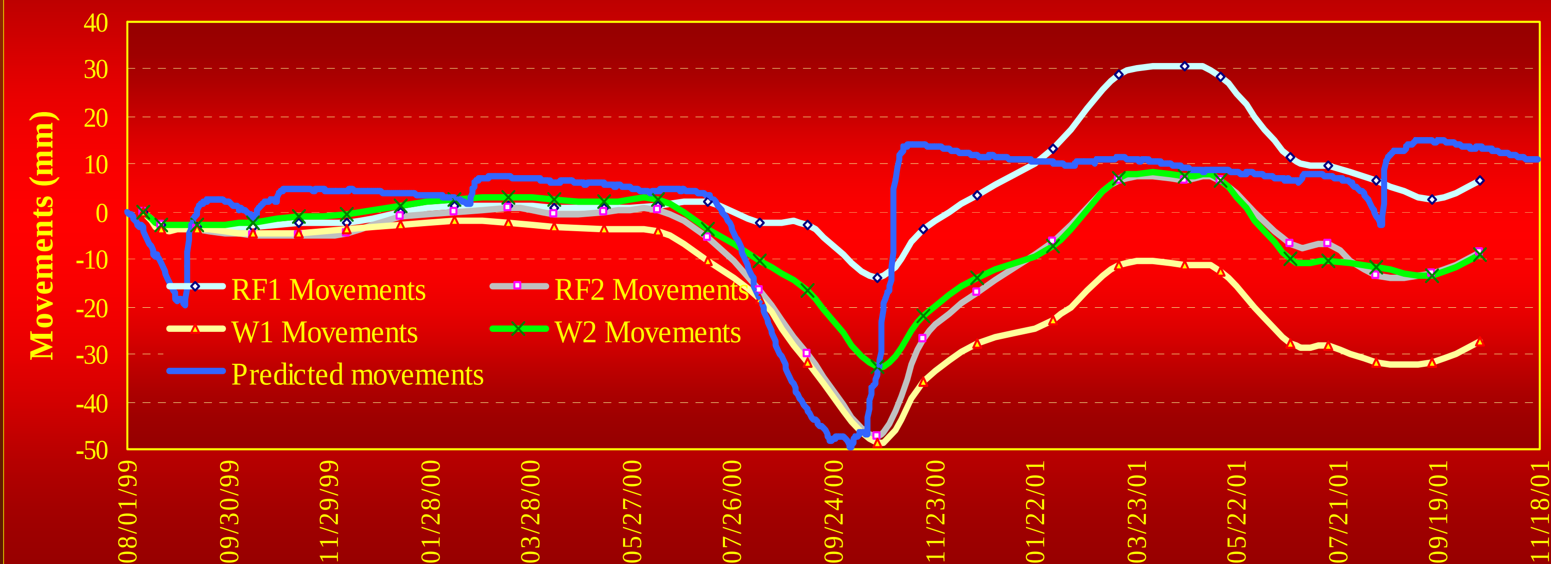
FOOTING MOVEMENT OVER TWO YEARS



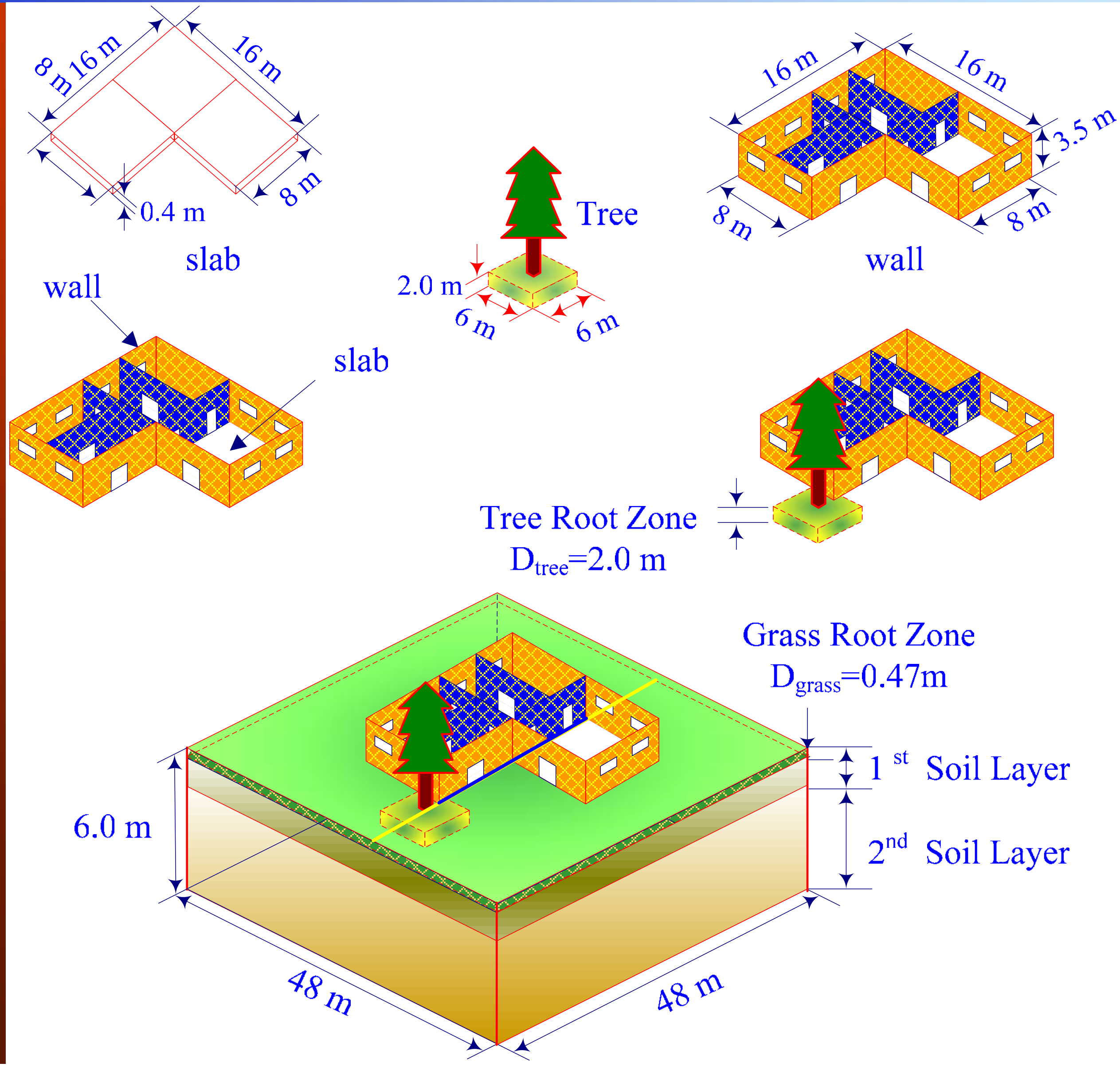
Weather of Arlington,Texas



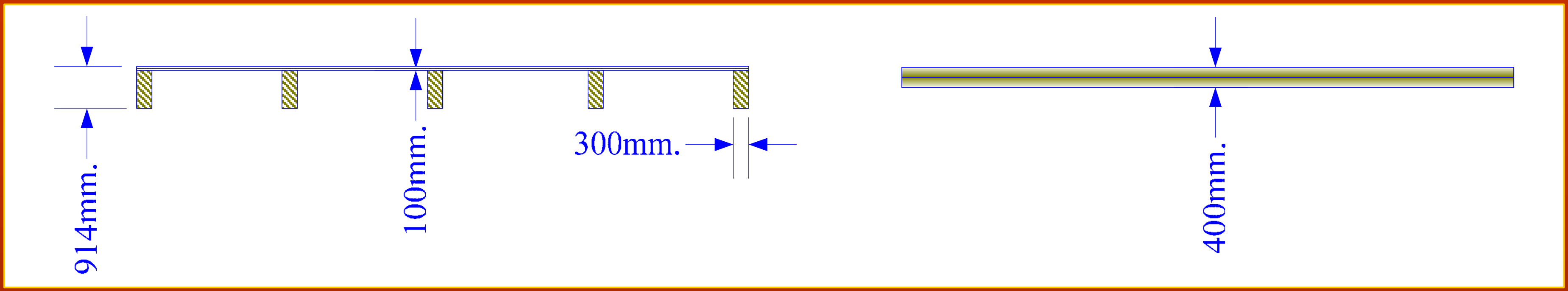
Comparison Between Predicted and Measured Movements



RESIDENTIAL BUILDING ON EXPANSIVE SOILS
AN EXAMPLE FOR CENTER LIFT CASE



DETERMINATION OF SLAB DIMENSION



WALLS:

EXTERIOR: BRICK

INTERIOR: STUD AND DRYWALL

SLAB:

FROM PTI MANUAL APPENDIX A.4 FOR AUSTIN, TEXAS;

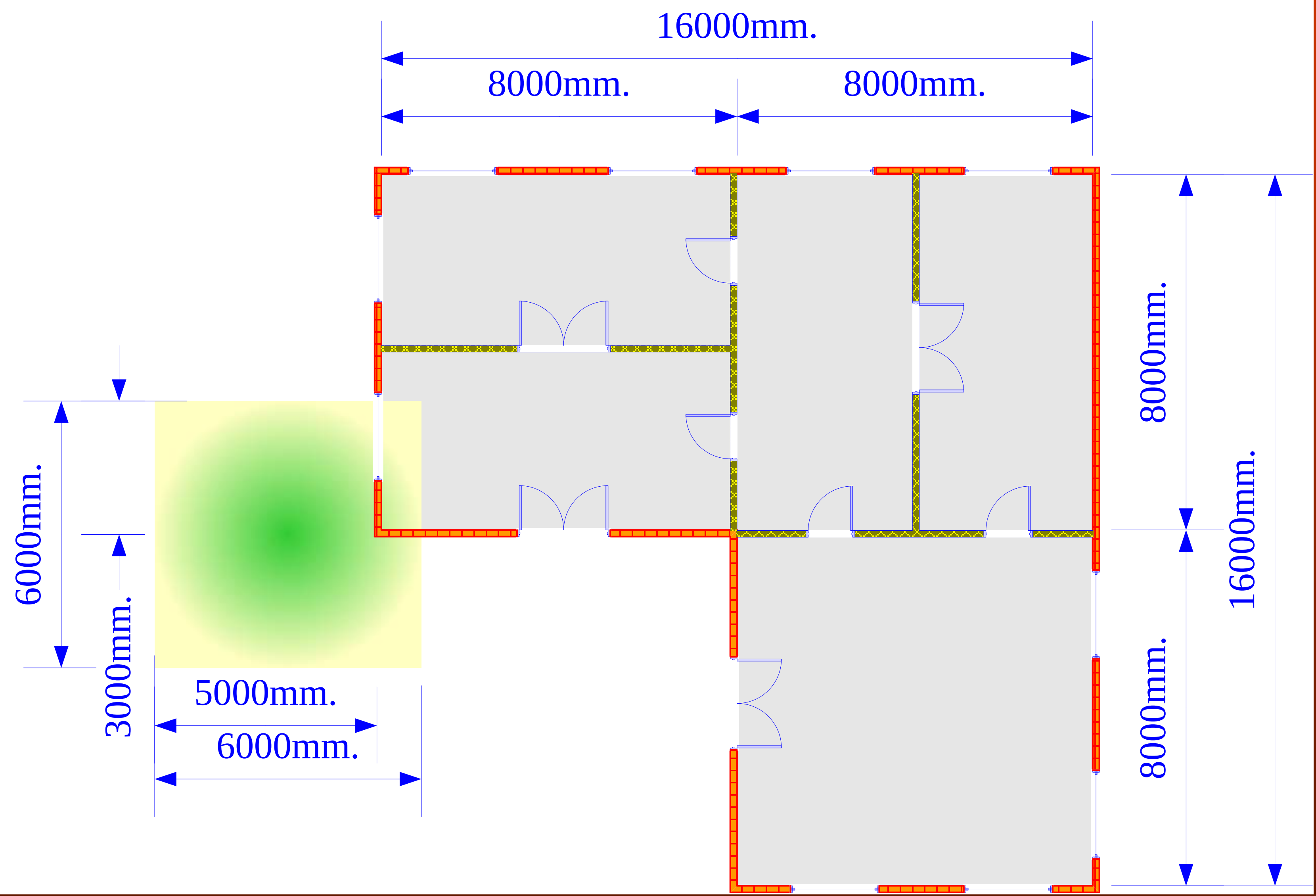
STIFFENING BEAMS: 12”X34” @15ft SPACING

EQUIVALENT SLAB WITH UNIFORM THICKNESS:

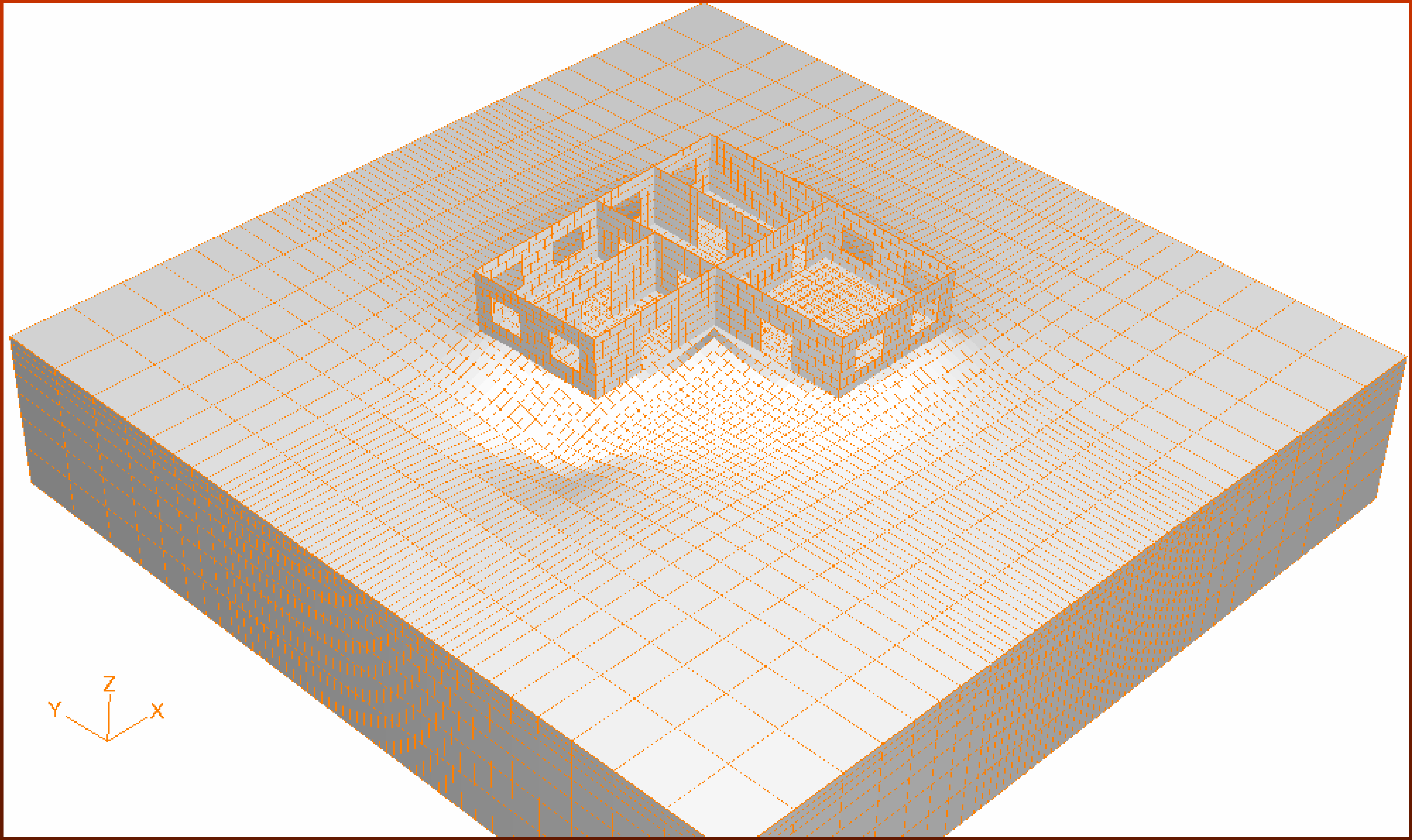
400mm (SAME MOMENT OF INERTIA AS ABOVE)

CENTER LIFT CASE

FLOOR PLAN OF THE BUILDING

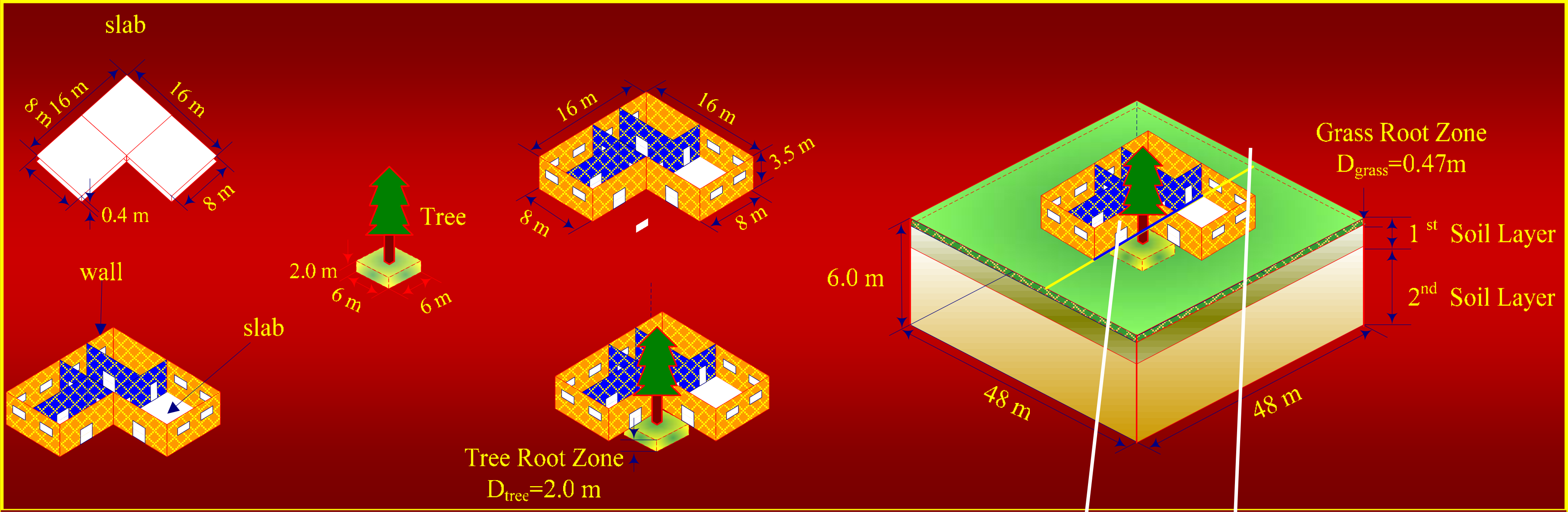


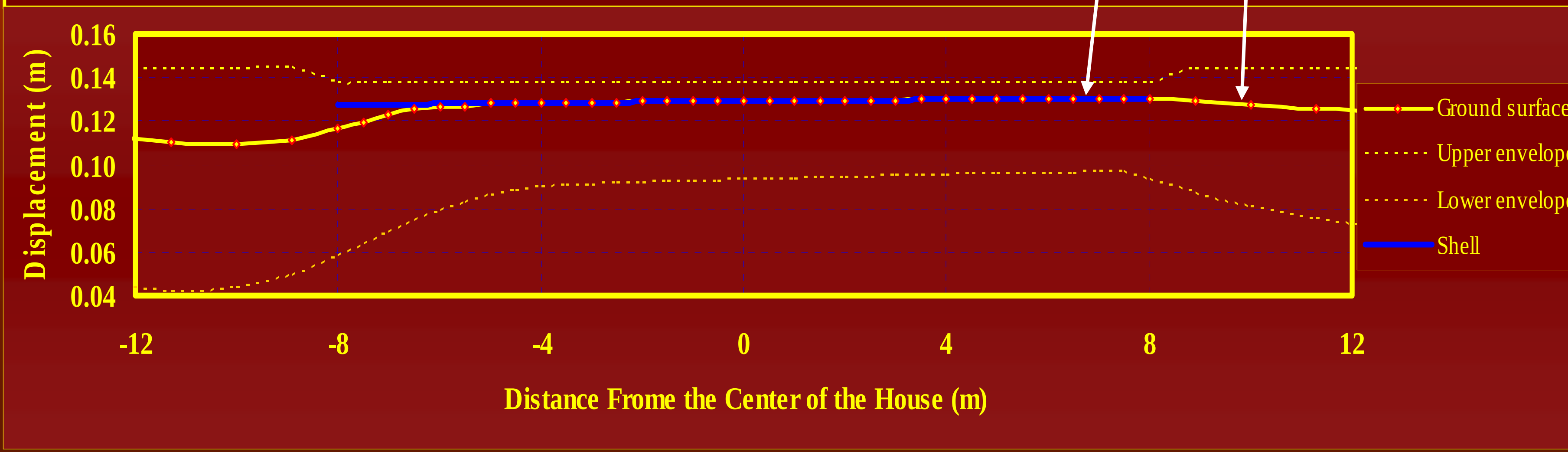
DEFORMATION OF THE SOIL AND THE SLAB



*** THIS PICTURE IS TAKEN FROM A MOVIE. A COMPLETE COPY OF THE MOVIE IS AVAILABLE FROM R. L. Lytton (r-lytton@civil.tamu.edu)**

DEFLECTION AND SEPERATION AT THE EDGE OF THE SLAB





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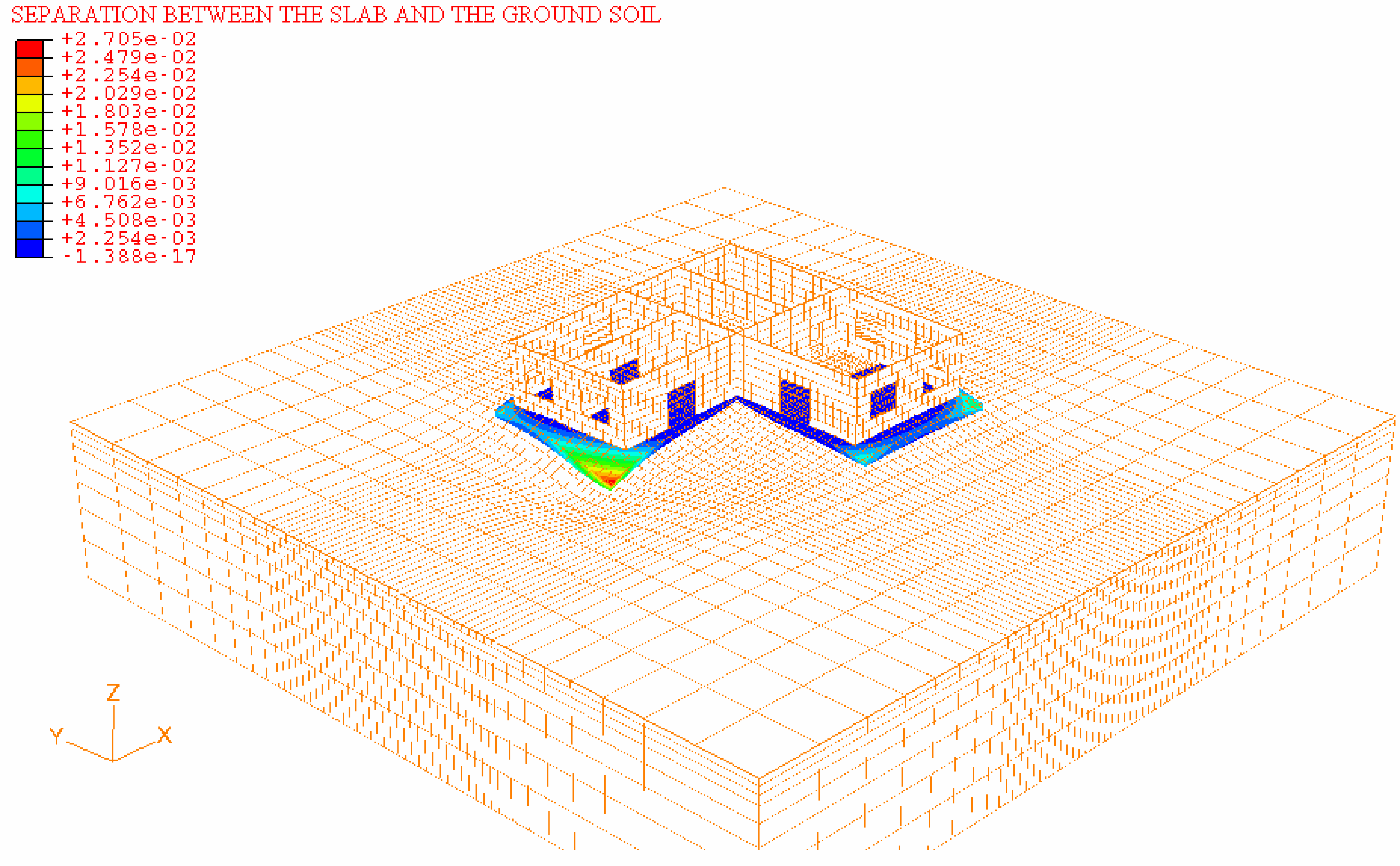
SEPARATION BETWEEN THE SLAB AND THE GROUND SOILS



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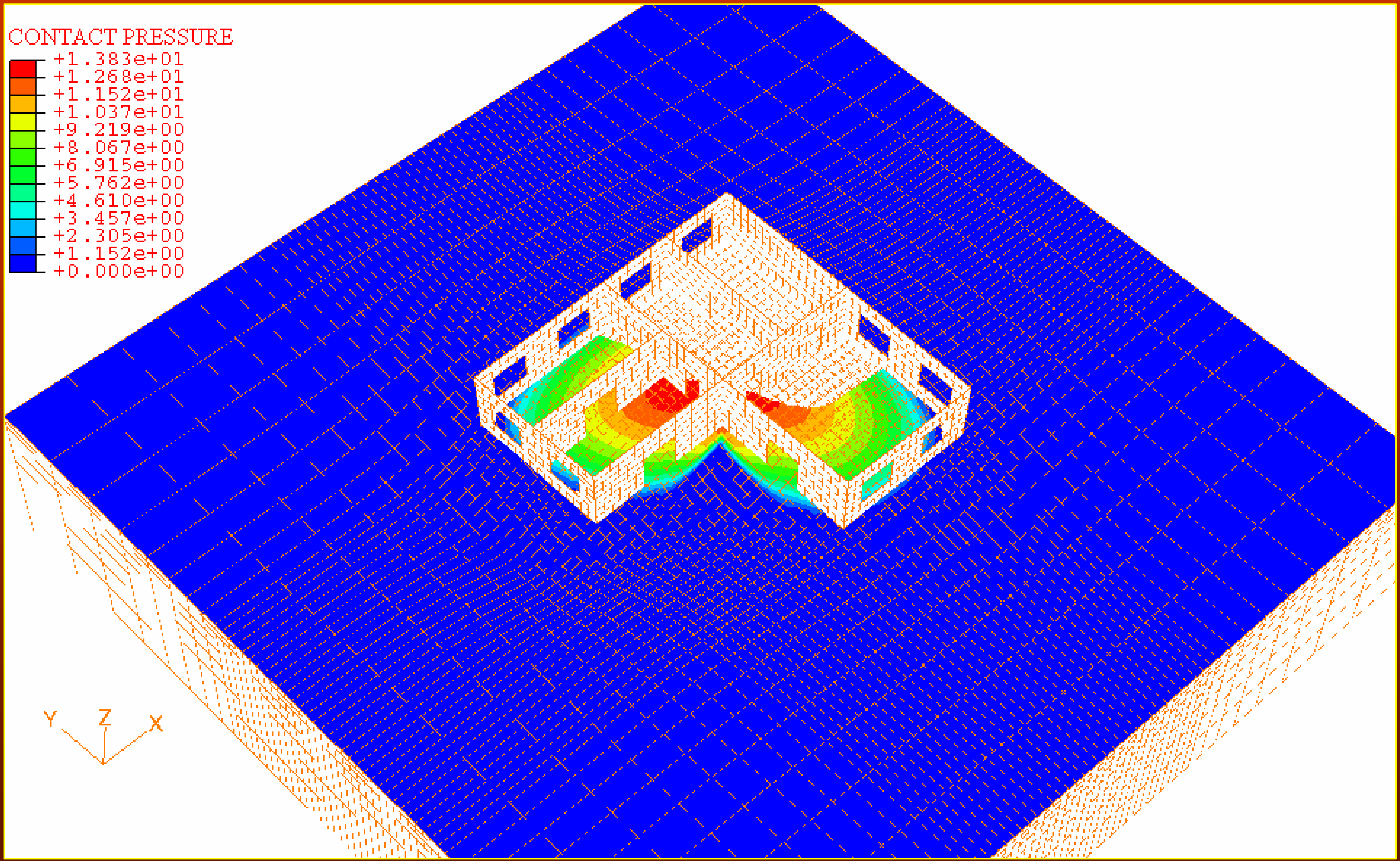
CONTACT PRESSURE BETWEEN THE SLAB AND THE GROUND SOILS



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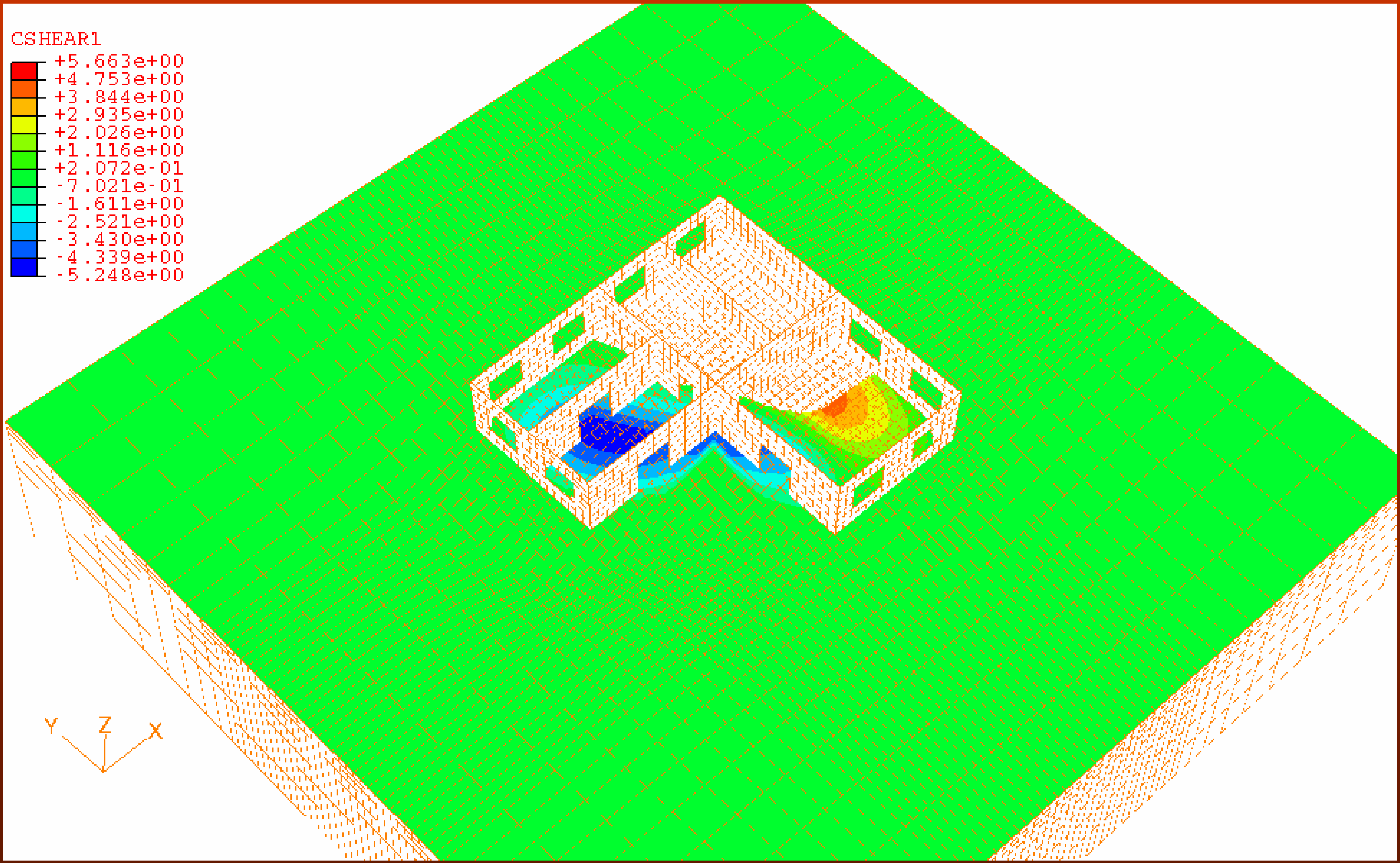
SHEAR FORCE ALONG X DIRECTION



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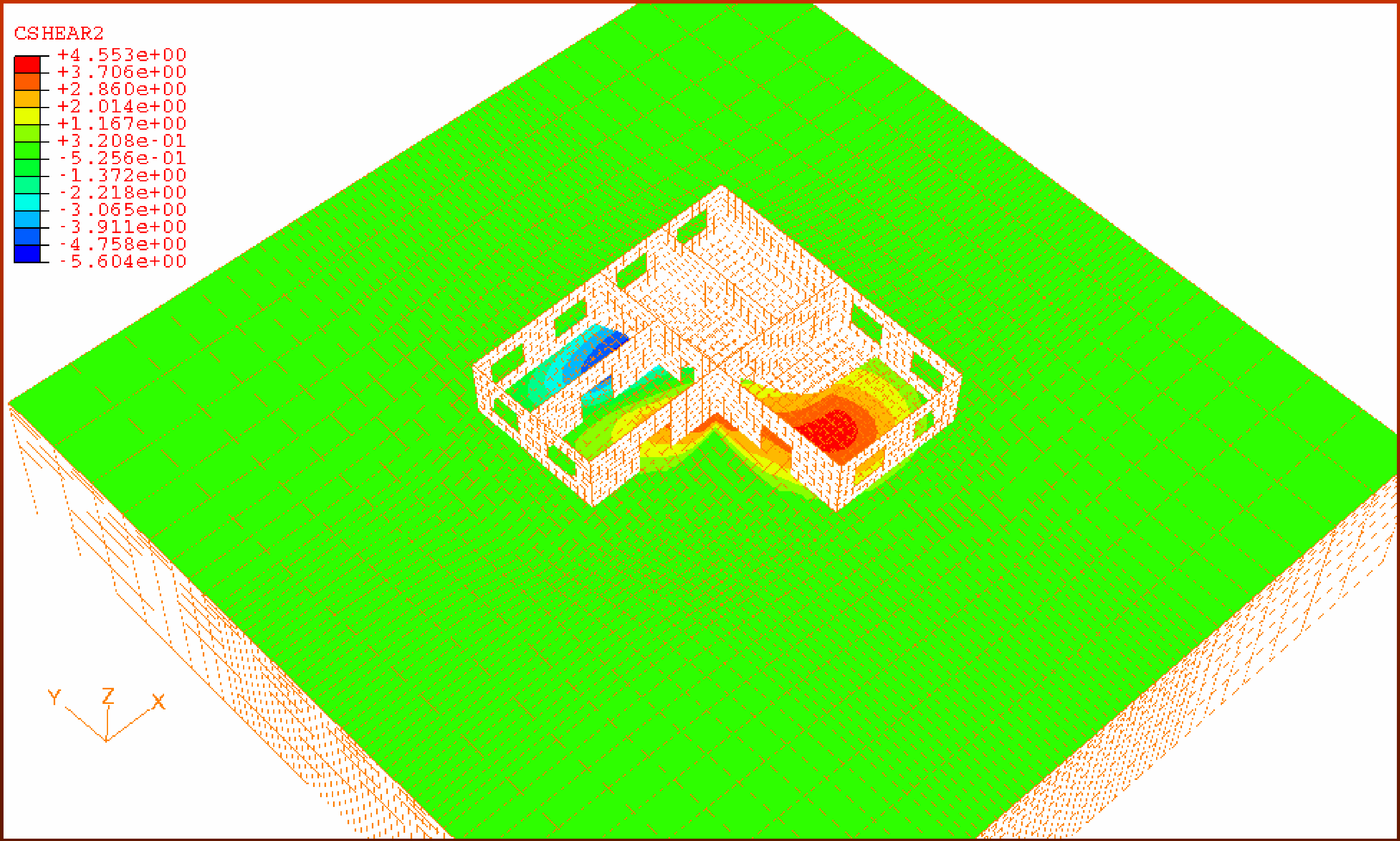
SHEAR FORCE ALONG Y DIRECTION



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RELATIVE SLIP ALONG X DIRECTION

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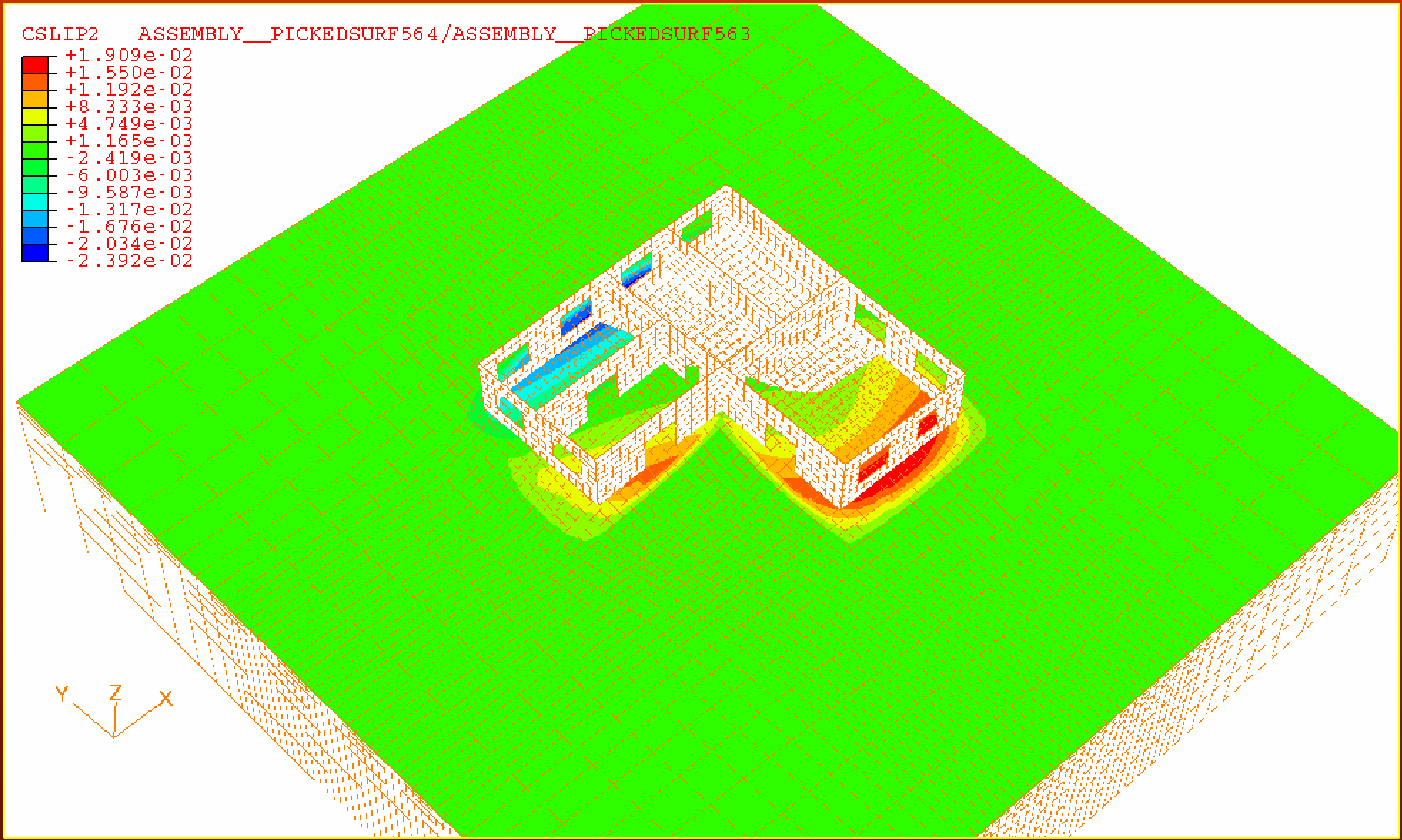

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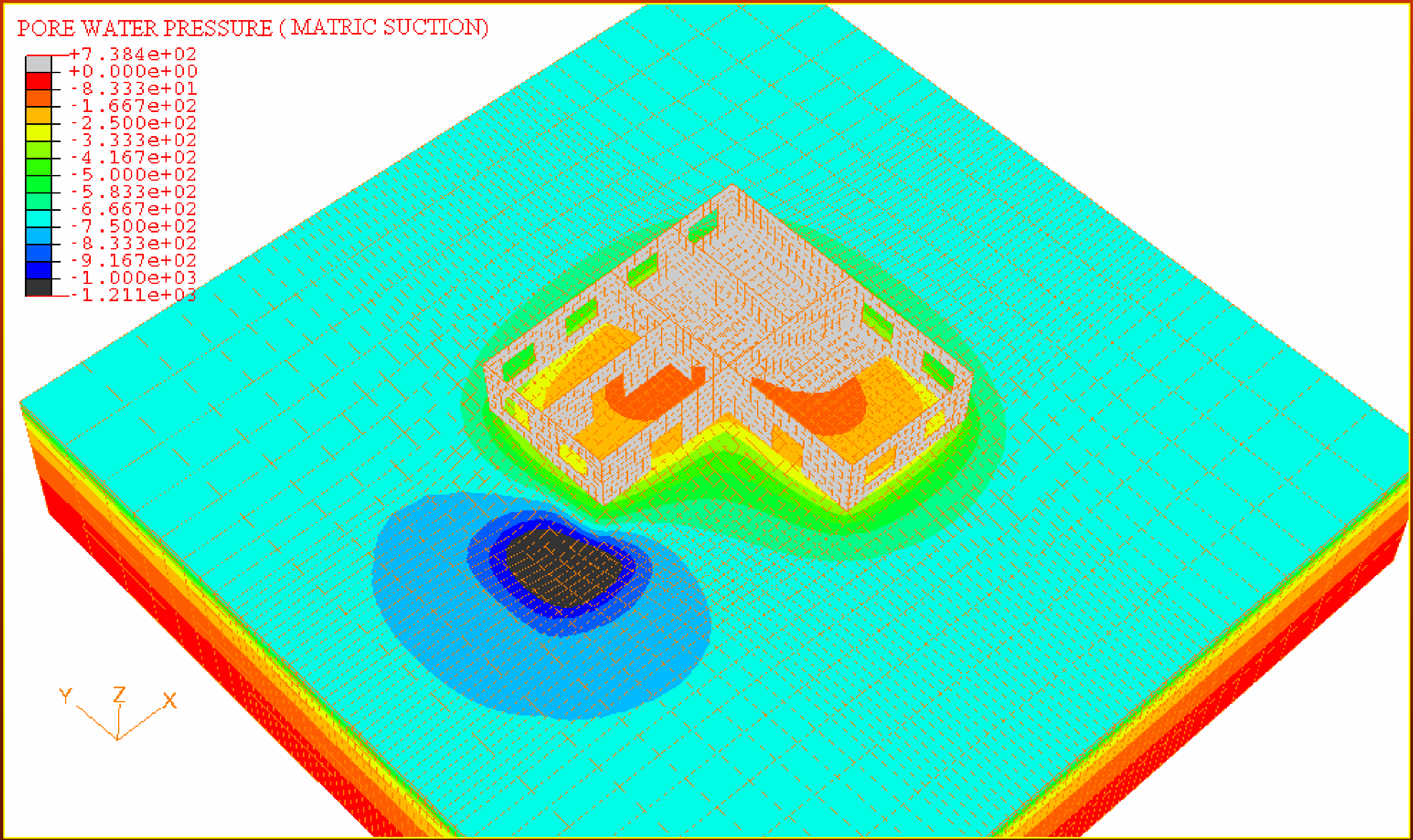
MATRIC SUCTION IN THE SOIL



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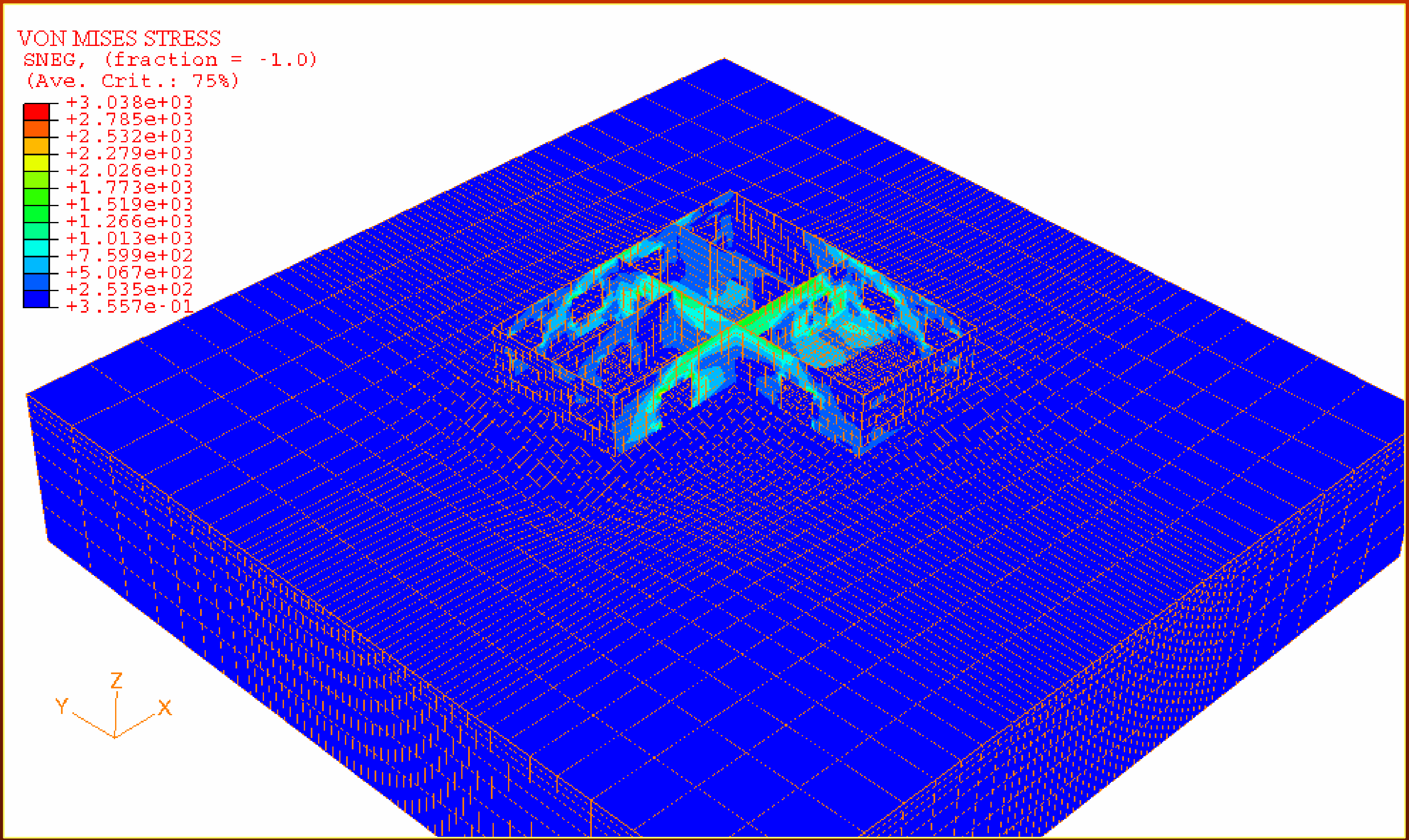
VON MISES STRESSES IN THE STRUCTRE



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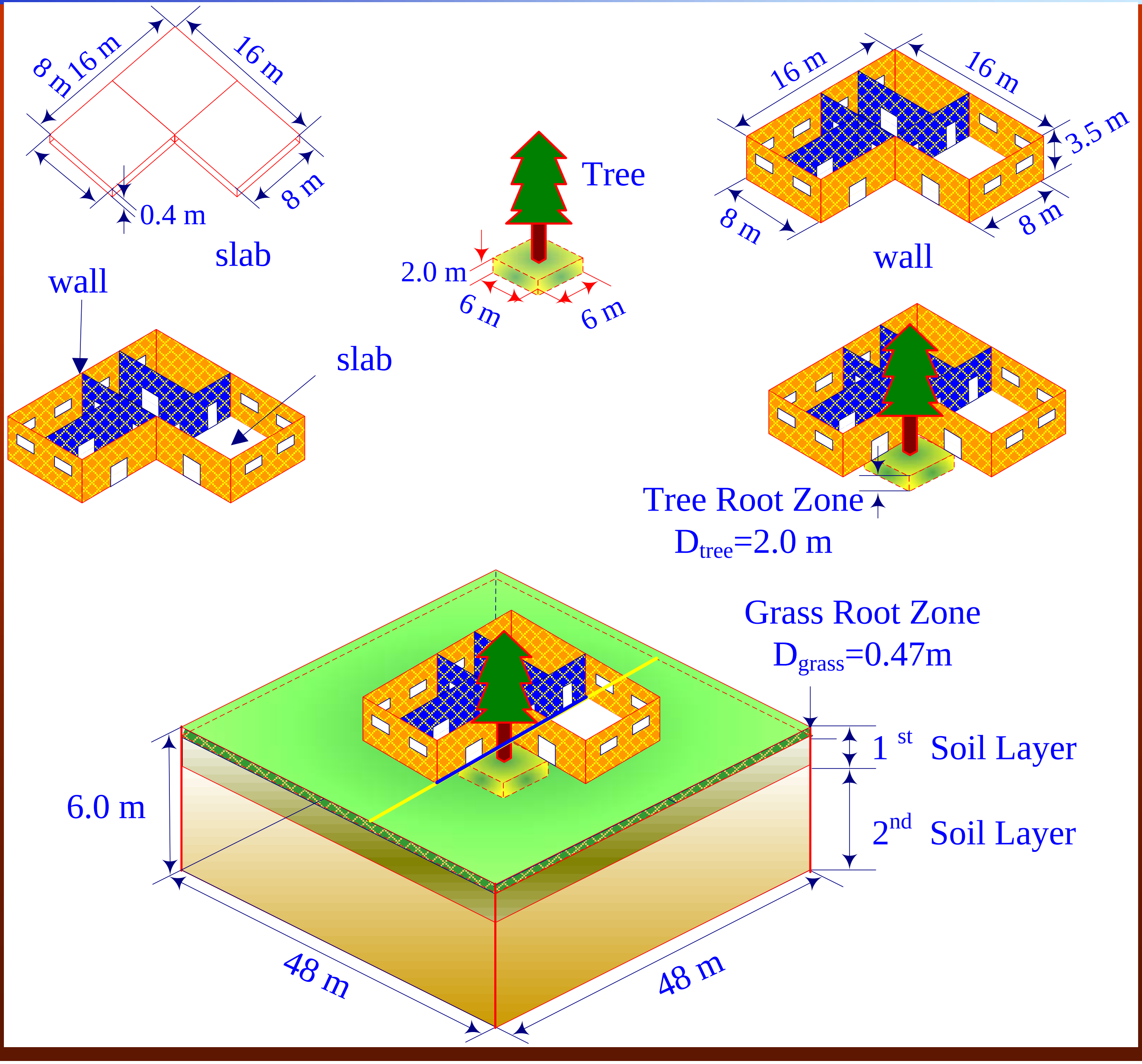
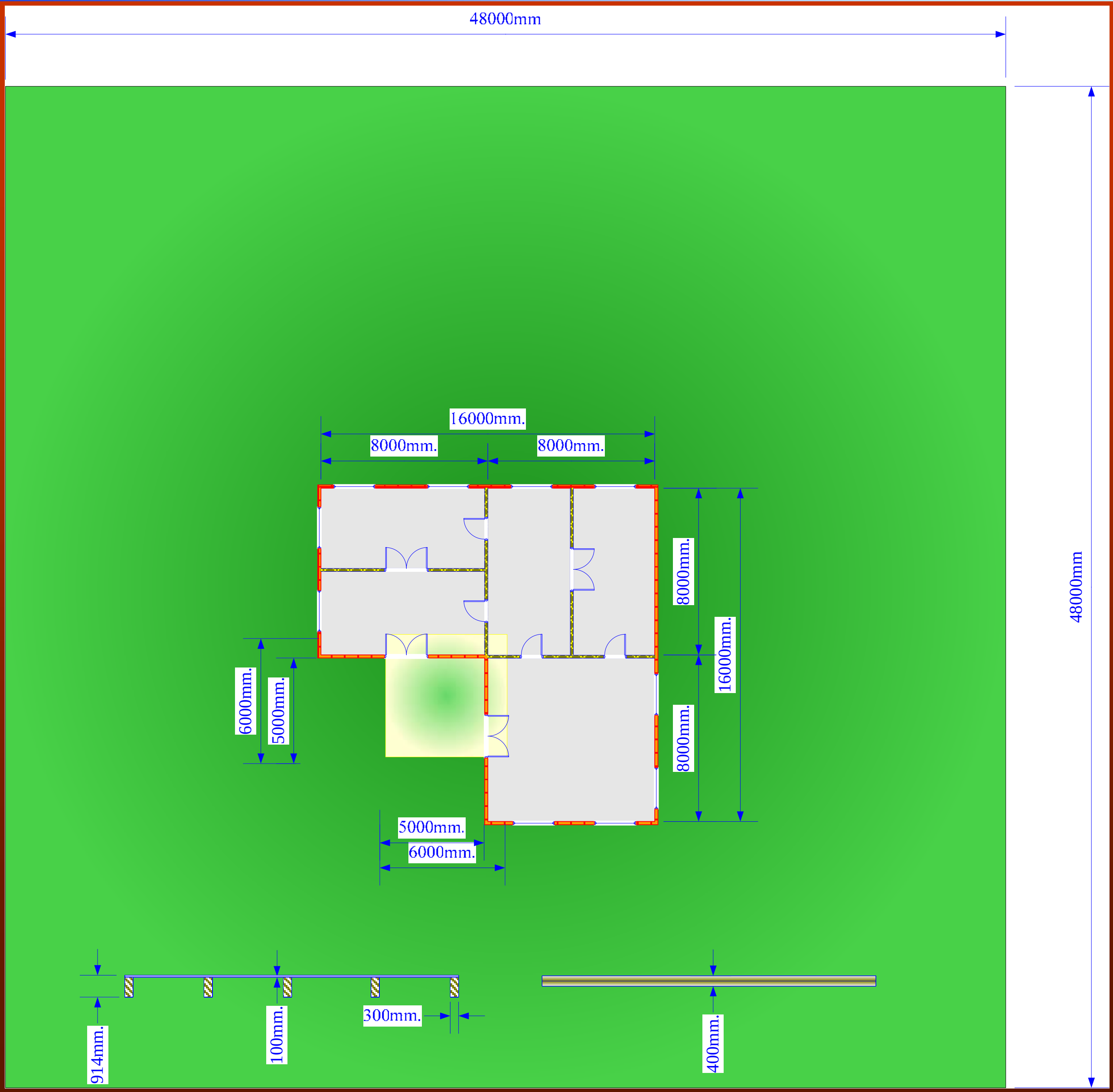
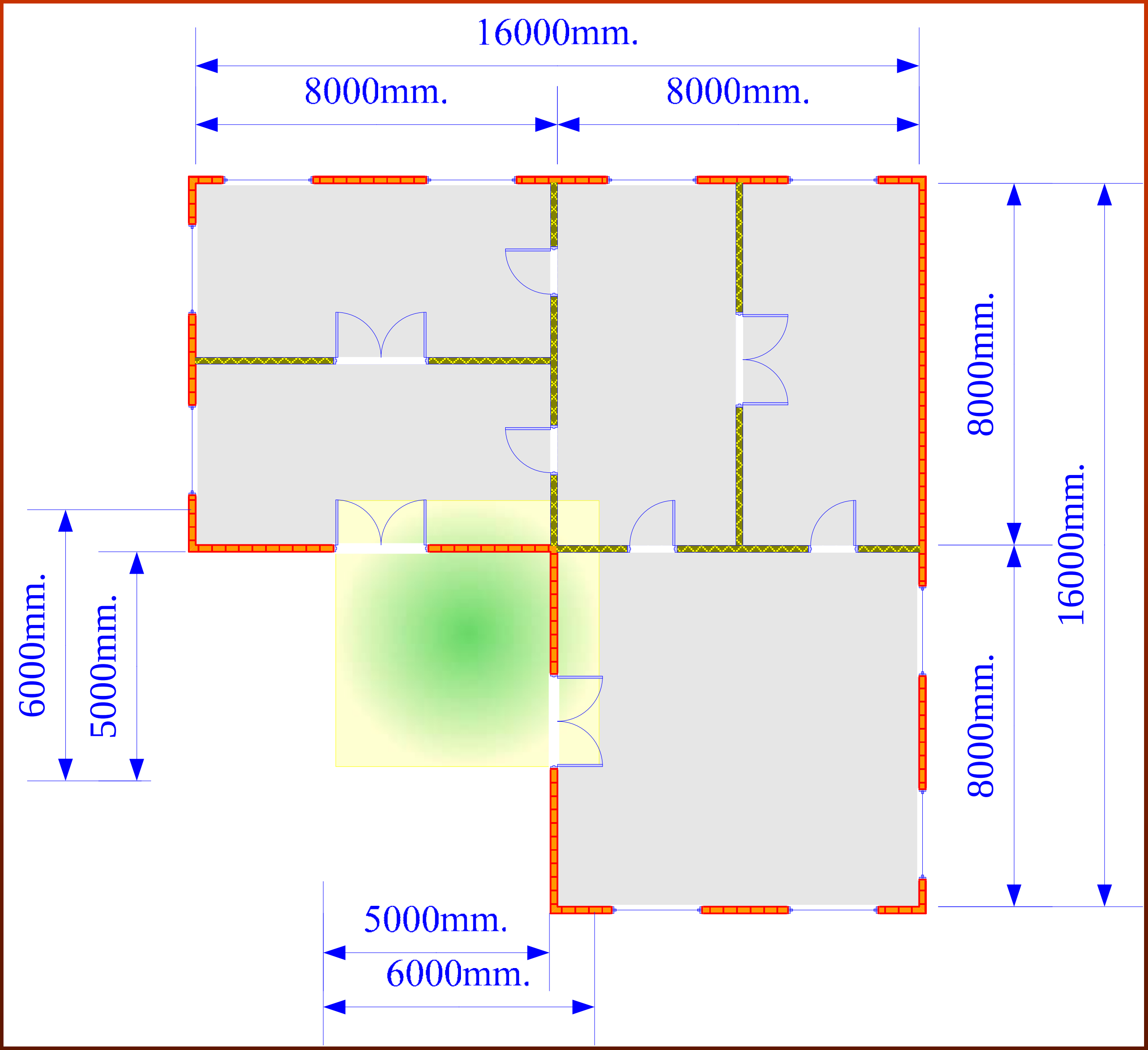
RESIDENCE USED IN THE SIMULATION
EDGE LIFT CASE



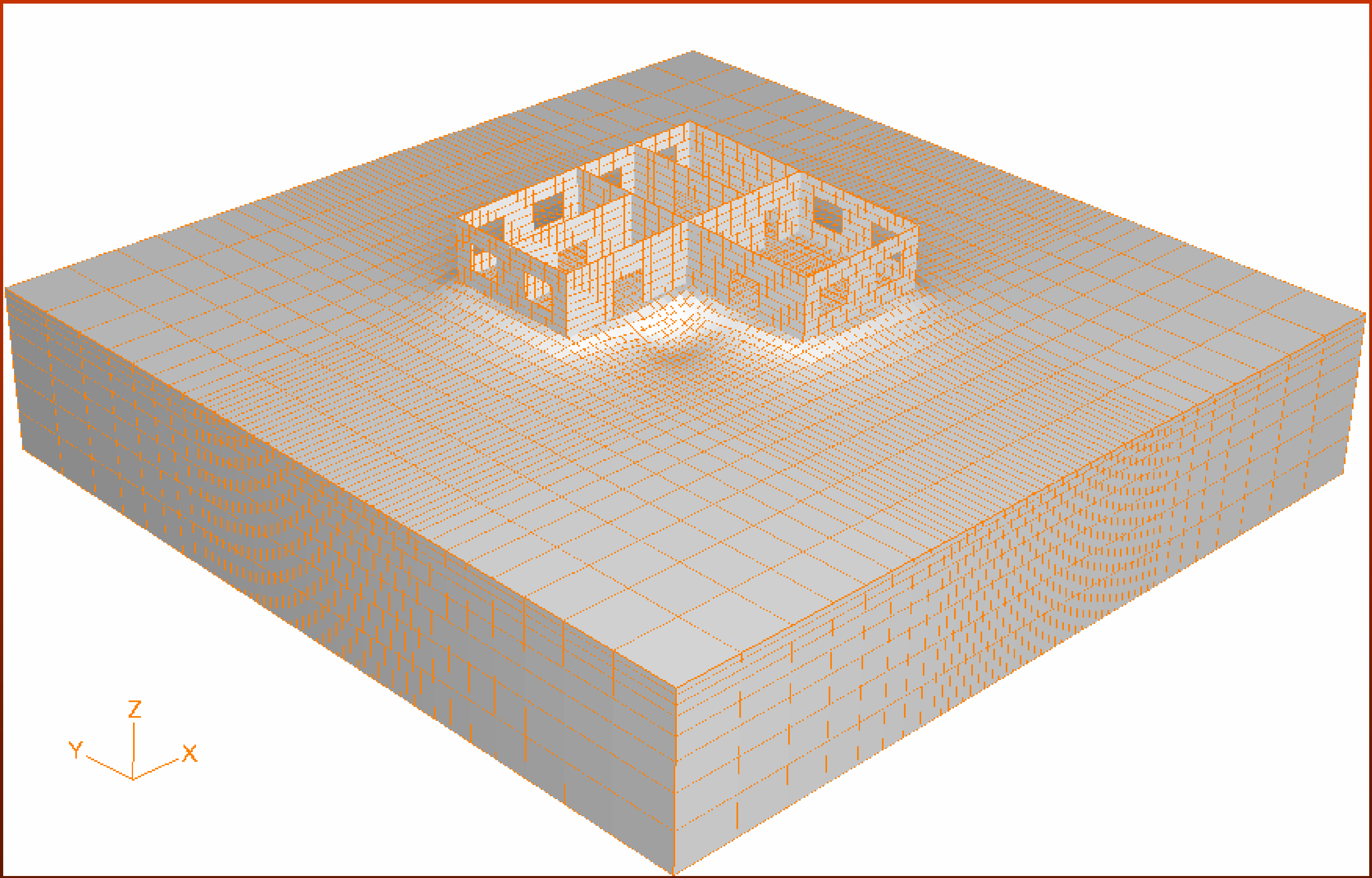
EDGE LIFT CASE



FLOOR PLAN OF THE BUILDING



DEFORMATION OF THE SOIL AND THE SLAB



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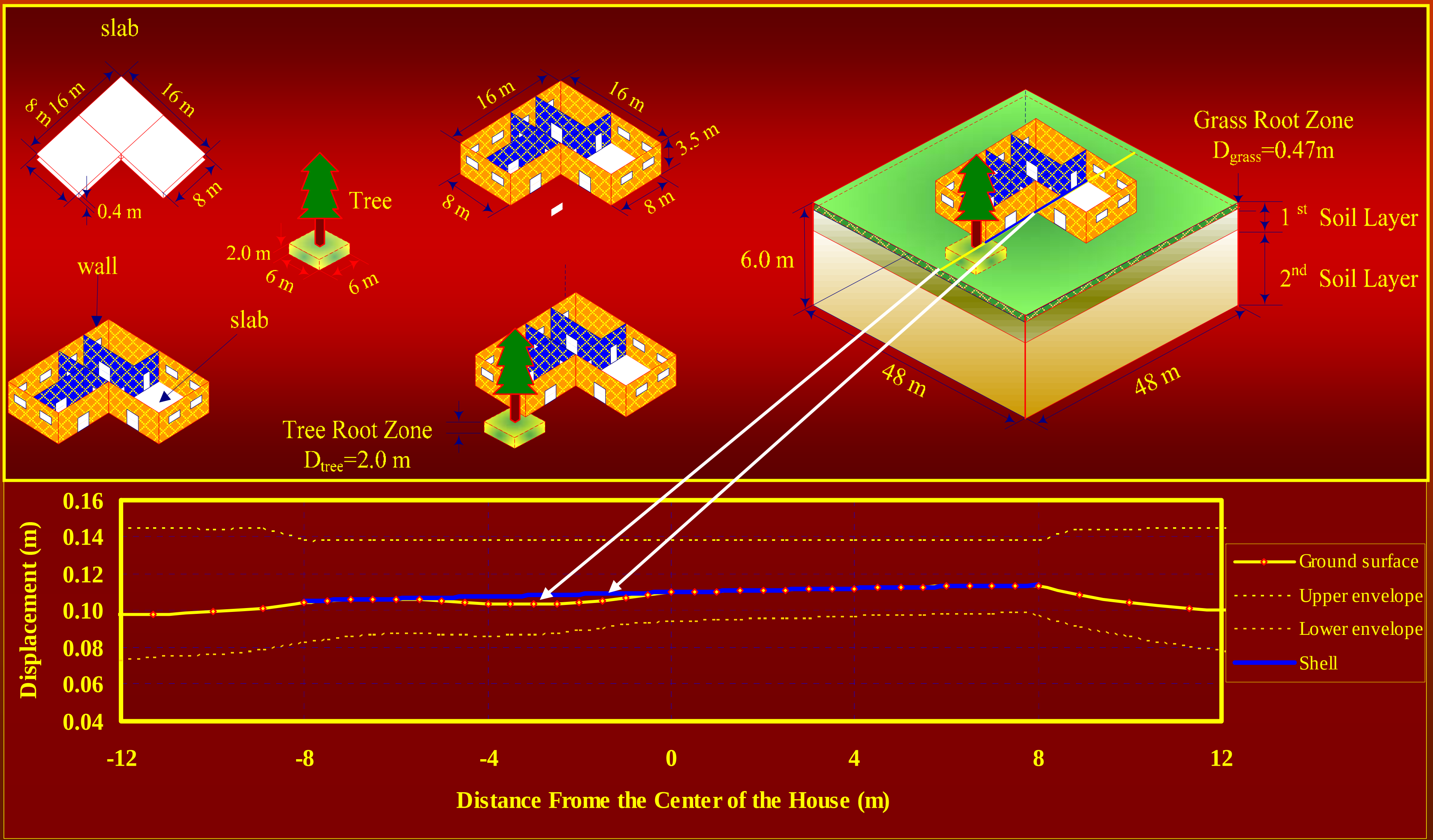

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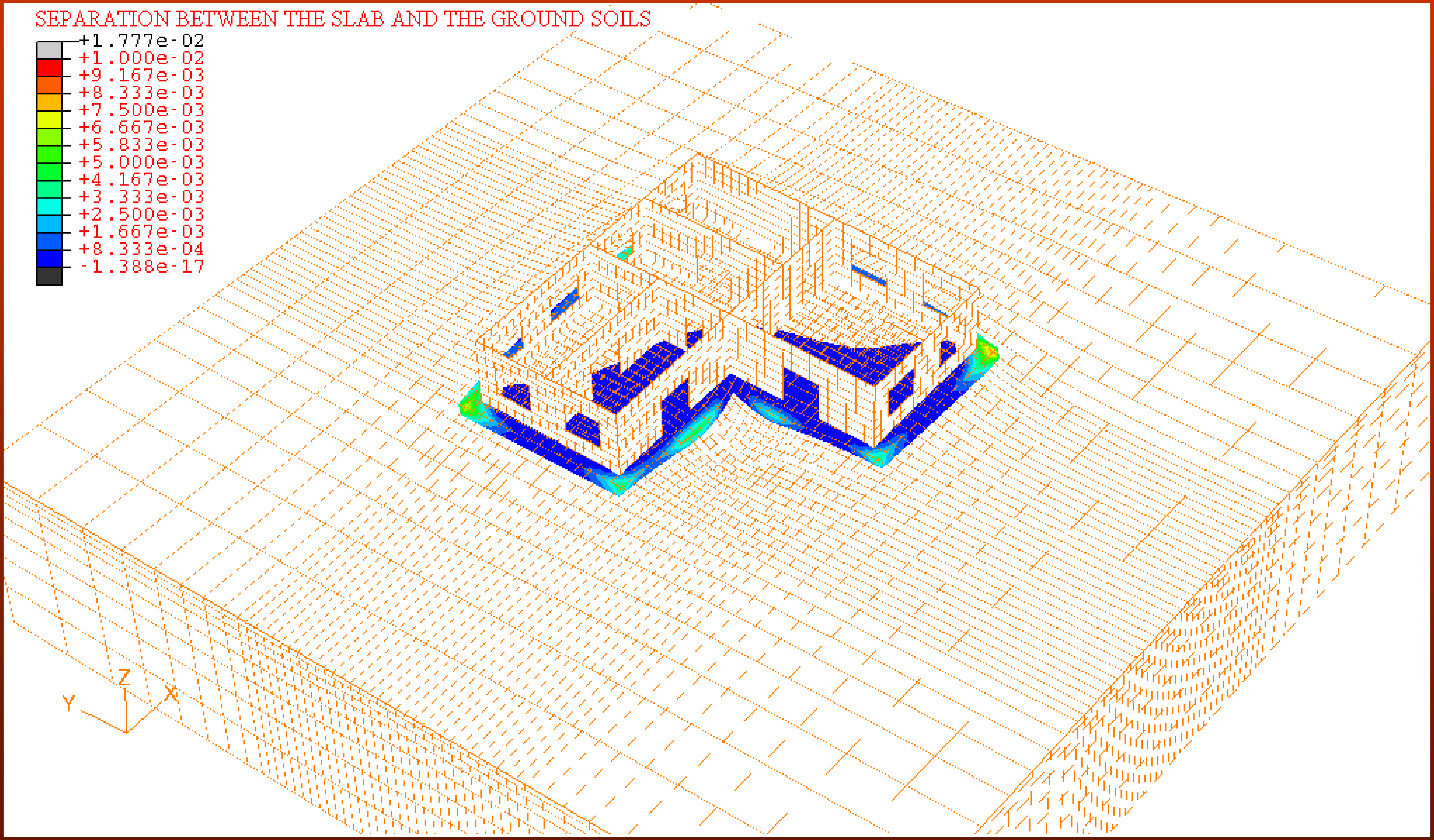
SEPARATION BETWEEN THE SLAB AND THE GROUND SOILS



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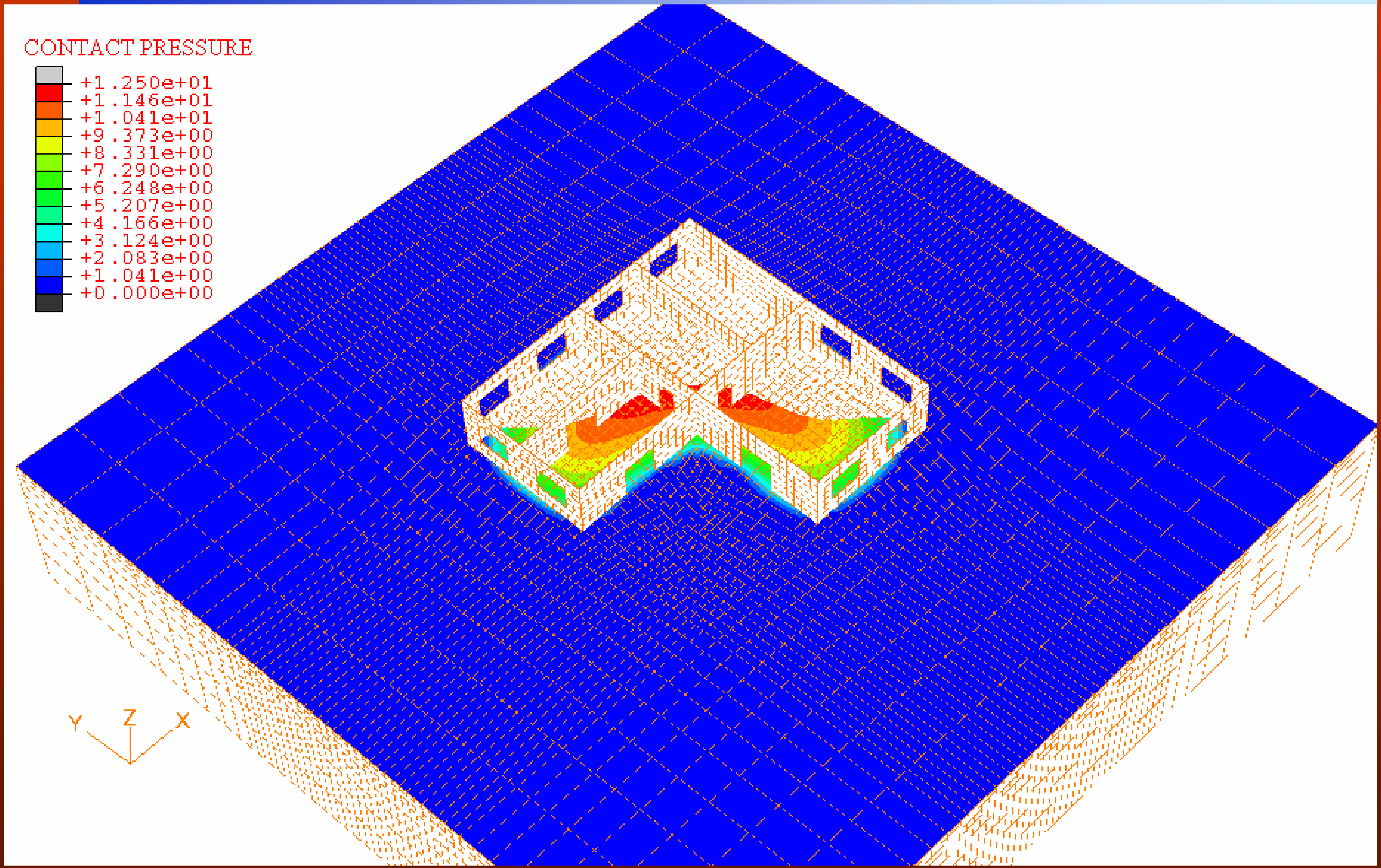
CONTACT PRESSURE BETWEEN THE SLAB AND THE GROUND SOILS



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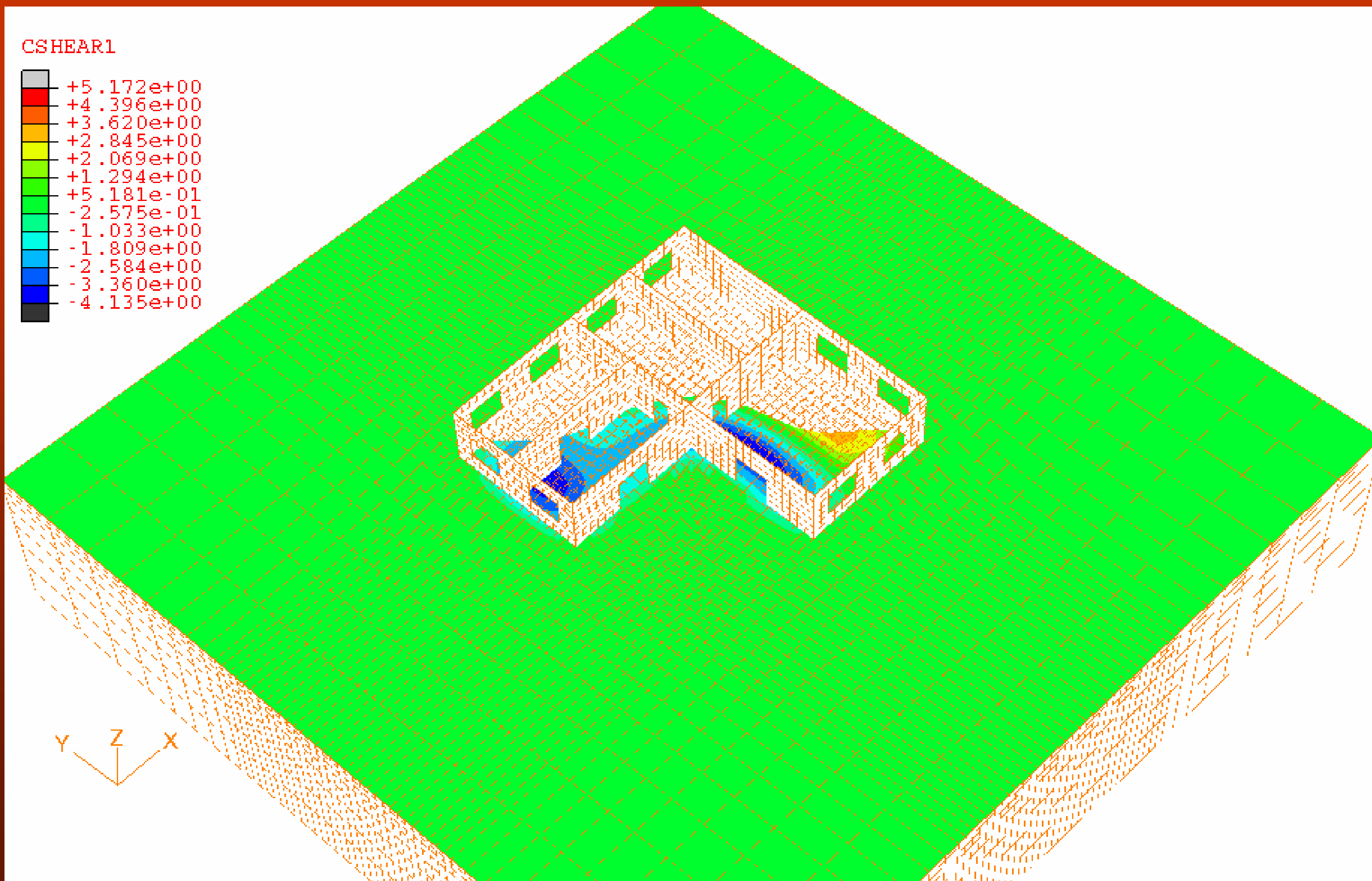
SHEAR FORCE ALONG X DIRECTION



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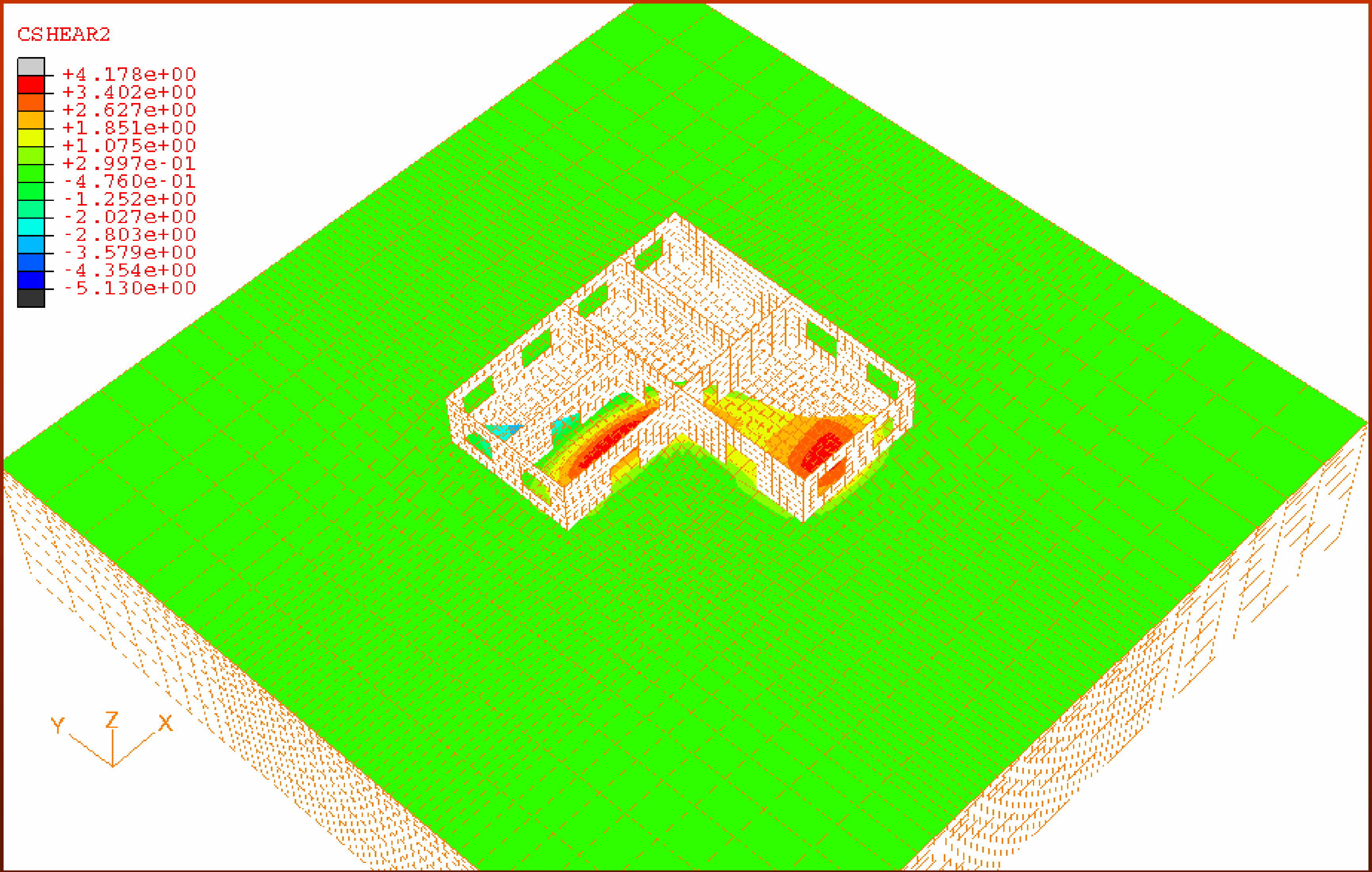

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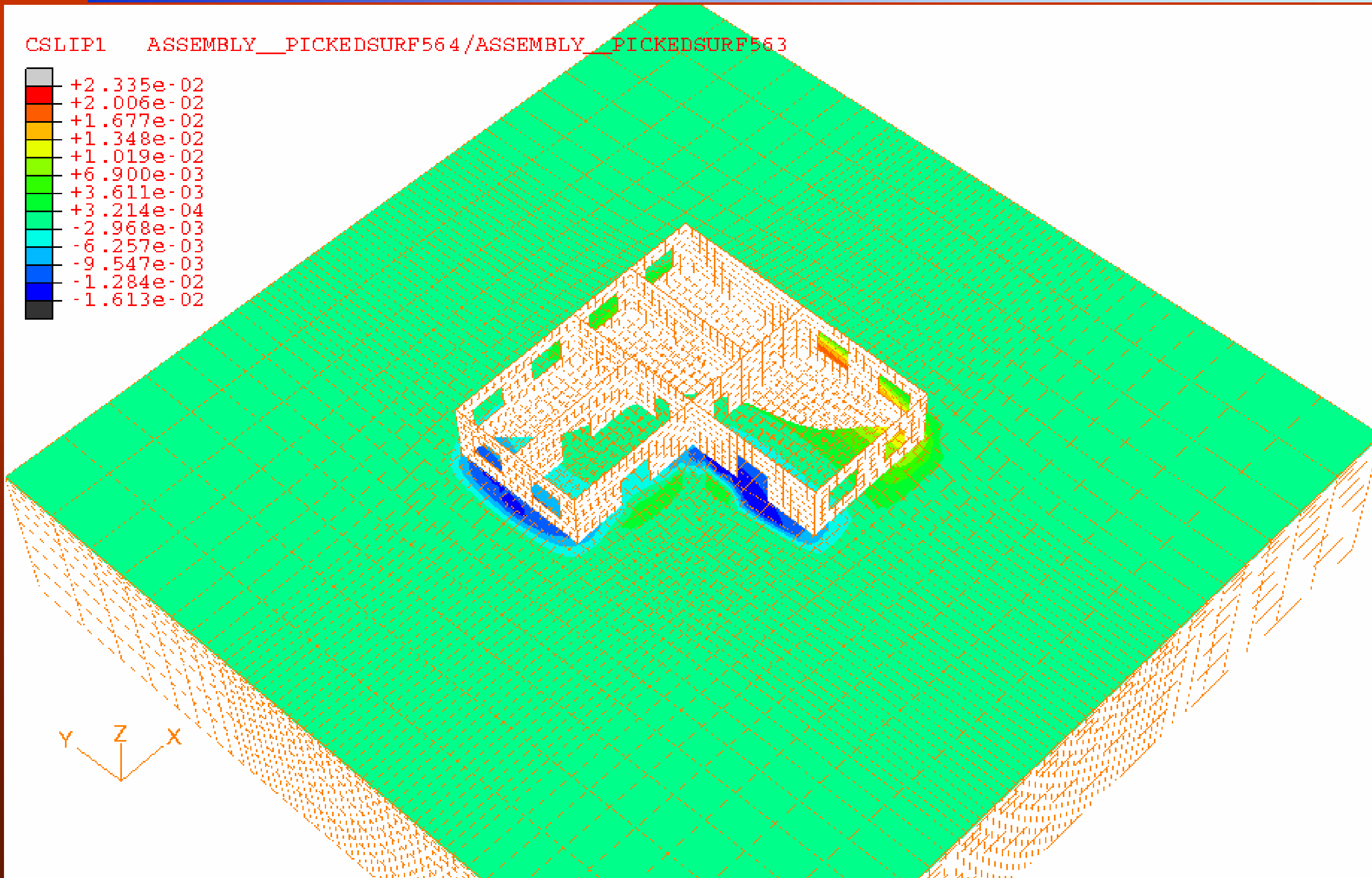
RELATIVE SLIP ALONG X DIRECTION



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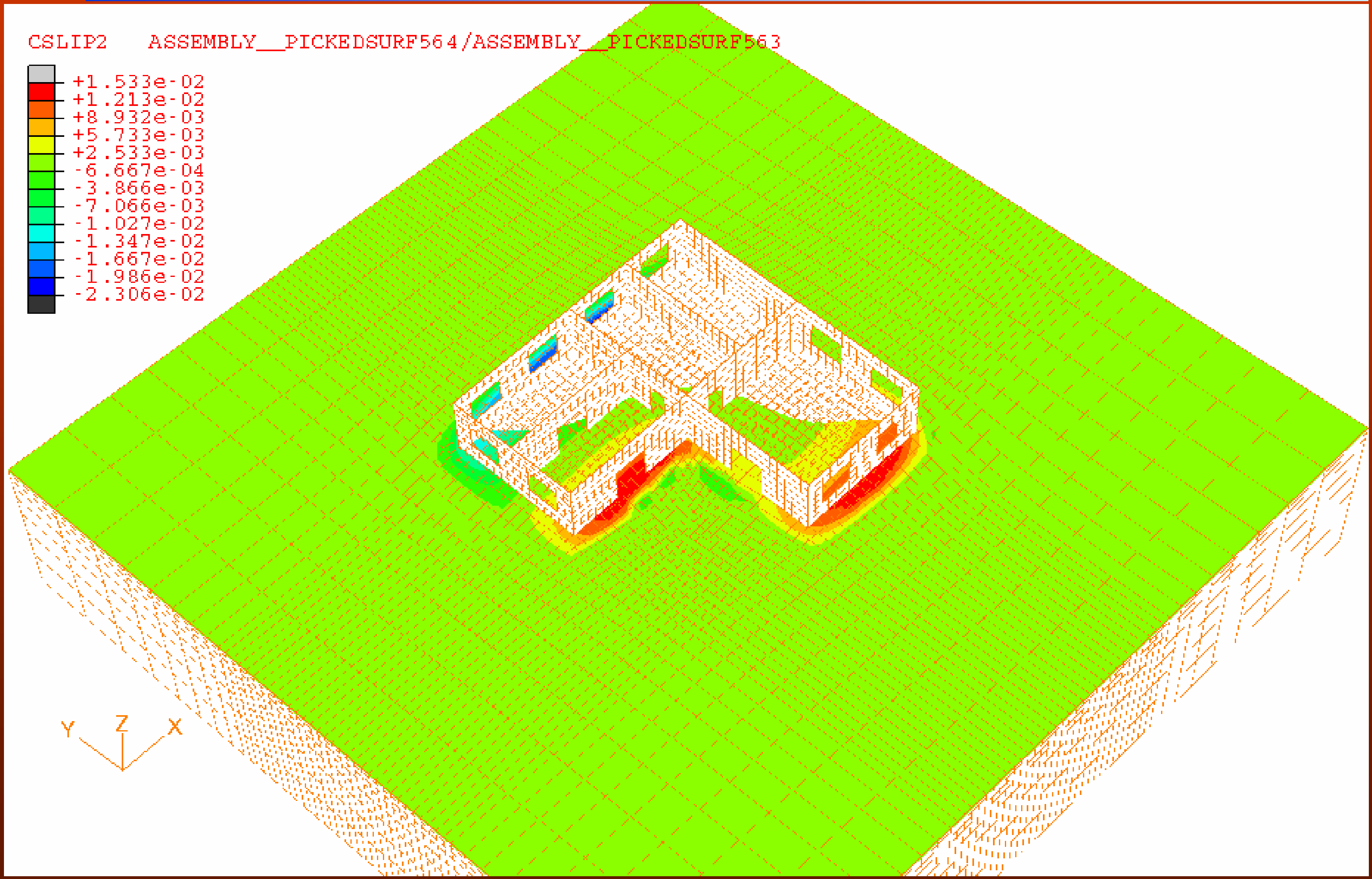

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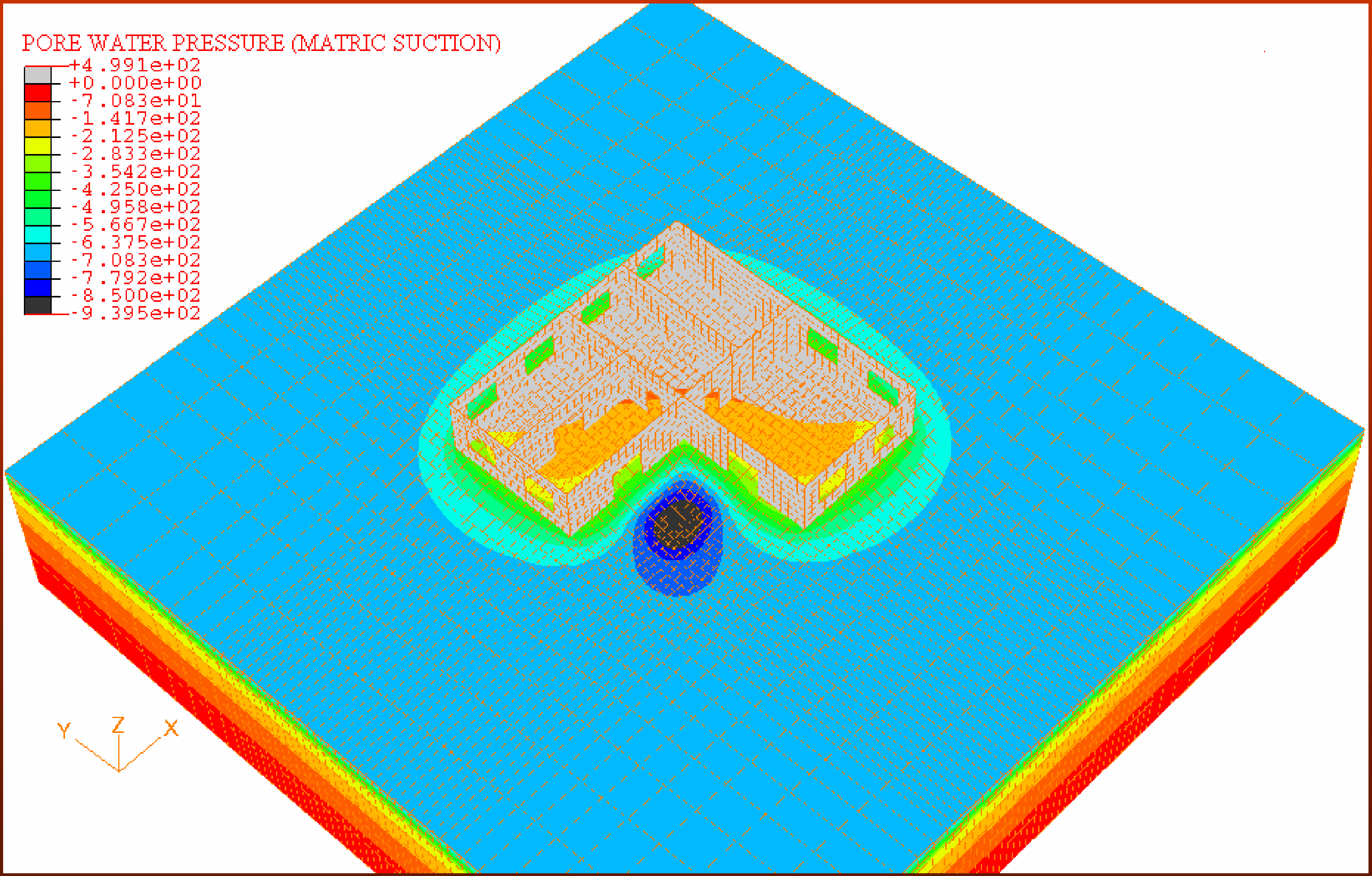
MATRIC SUCTION IN THE SOIL



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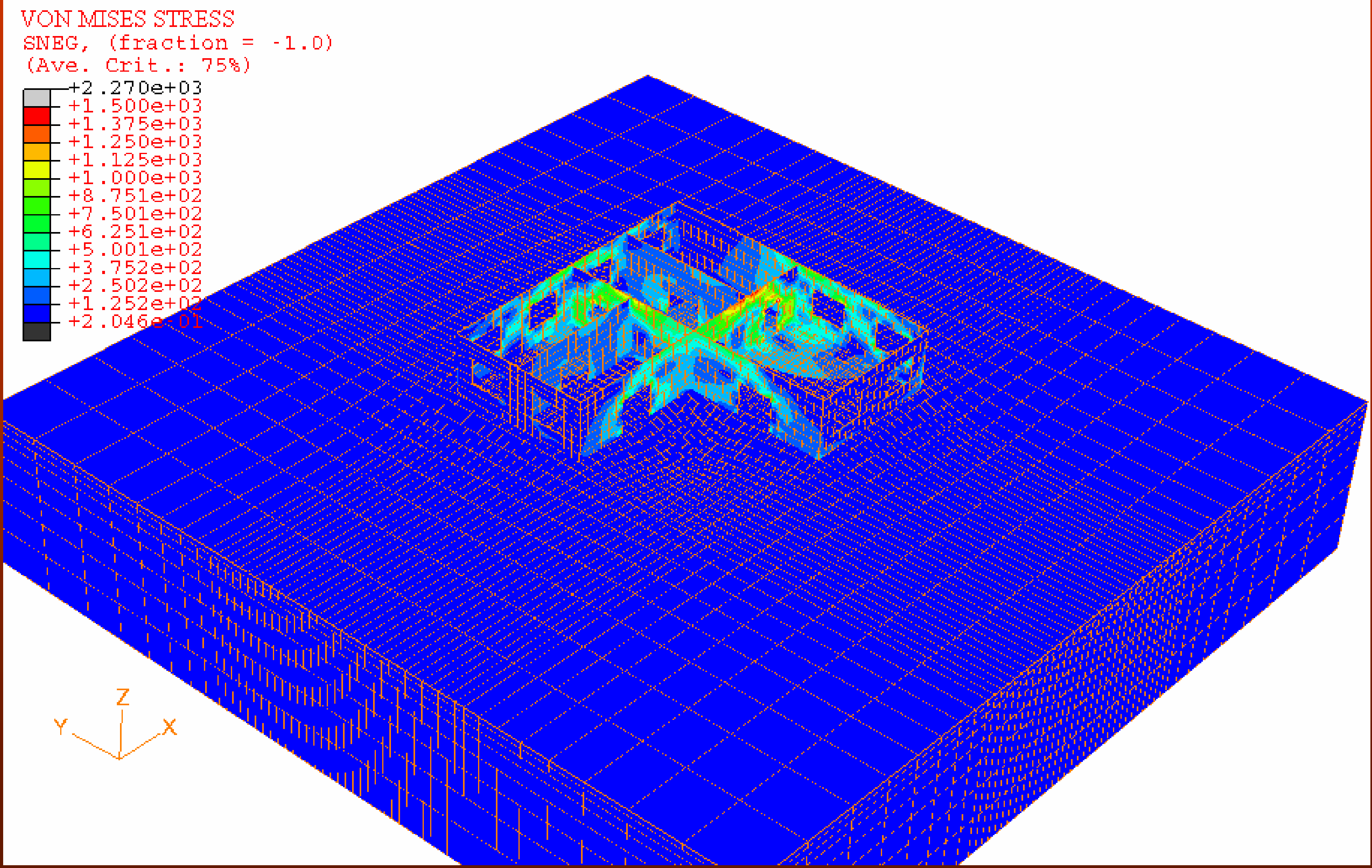

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CONCLUSIONS

- READILY AVAILABLE HISTORIC WEATHER DATA SUCH AS DAILY TEMPERATURE, SOLAR RADIATION, RELATIVE HUMIDITY, WIND SPEED AND RAINFALL AS INPUT;
- DIFFERENT SIMULATION METHODS FOR DIFFERENT BOUNDARY CONDITIONS SUCH AS TREE, GRASS, AND BARE SOILS;
- THE COUPLED HYDRO-MECHANICAL STRESS ANALYSIS ARE USED TO SIMULATE THE VOLUME CHANGE OF EXPANSIVE SOILS;

CONCLUSIONS

- “PSEUDO MOISTURE VARIATION SIMULATION” TECHNIQUE IS USED TO SIMULATE THE BEHAVIOR OF SLAB AND GROUND SOILS IN ONE PROGRAM
- CONTACT (JOINTED) ELEMENTS ARE USED TO SIMULATE THE SOIL-STRUCTURE INTERACTION;
- GENERAL SHELL ELEMENTS ARE USED TO ANALYZE THE STRUCTURE BEHAVIORS;
- MOMENT-CURVATURE CURVES FOR CONCRETE CROSS SECTIONS WITH BONDED AND UNBONDED REINFORCING IS PROPOSED TO SIMULATE DAMAGE TO THE STRUCTURE.

COMMENTS/ QUESTIONS

……….THANK YOU