CE394M Advanced Analysis in Geotechnical Engineering: Introduction

Krishna Kumar

University of Texas at Austin

krishnak@utexas.edu

February 1, 2019

Overview

1. Geotechnical modeling
   - Complexity in Geotechnical modeling
   - Classical vs advanced analysis
2. Numerical methods for differential equations
   - Direct method: Matrix analysis of structures
3. Governing equations in stress-deformation analysis
   - Stress equilibrium
   - Compatibility condition
   - Stress-strain relationship

Geotechnical modeling of the complex world

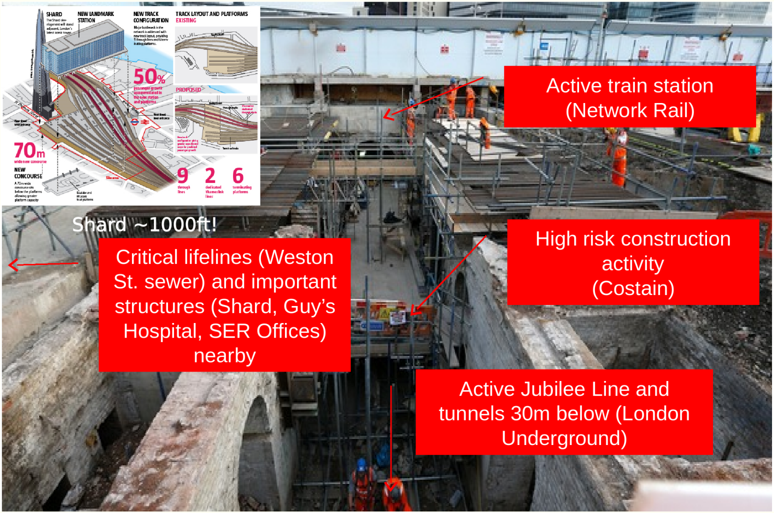


Fig. London Bridge Station, London, UK

Geotechnical modeling of the complex world

Fig. London Victoria station upgrade, London, UK

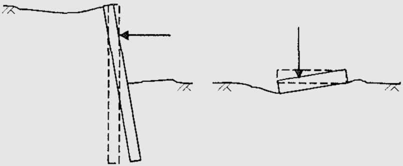
Fig. London Victoria station upgrade, London, UK

Movements must be estimated, both of the structure and of the ground. This is particularly important if there are adjacent buildings and for sensitive services. For example, if an excavation is to be made in an urban area close to existing services and buildings, one of the key design constraints is the effect that the excavation has on the adjacent structures and services. It may be necessary to predict any structural forces induced in these existing structures and/or services.

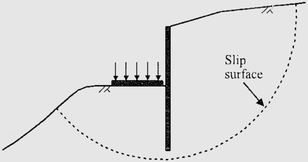
Geotechnical modeling of the complex world

Fig. London Victoria station upgrade, London, UK

When designing any geotechnical structure, the engineer must ensure that it is stable. Stability can take several forms. Firstly, the structure and support system must be stable as a whole. There must be no danger of rotational, vertical or translational failure (**local stability**). Secondly, **overall stability** must be established. For example, if a retaining structure supports sloping ground, the possibility of the construction promoting an overall slope failure should be investigated.

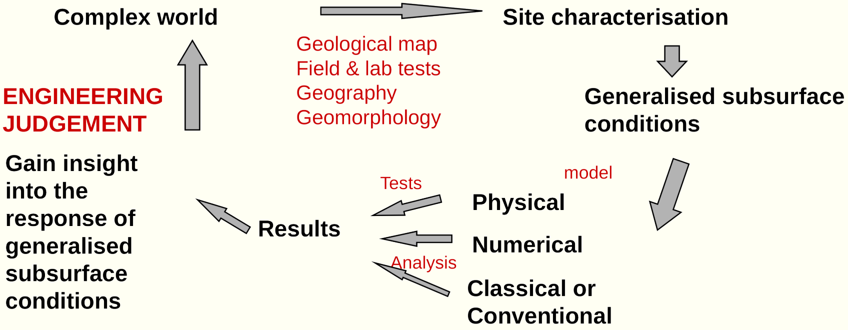


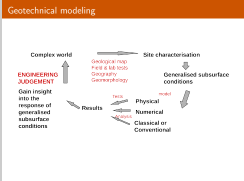
Local stability



Overall stability

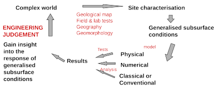
Geotechnical modeling





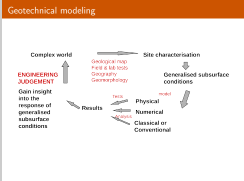
Design requirements: Before the design process can begin, a considerable amount of information must be assembled. The basic geometry and loading conditions must be established. These are usually defined by the nature of the engineering project.

A geotechnical site investigation is then required to establish the ground conditions. Both the soil stratigraphy and soil properties should be determined. In this respect it will be necessary to determine the strength of the soil and, if ground movements are important, to evaluate its stiffness too. The position of the ground water table and whether or not there is underdrainage or artesian conditions must also be established. The possibility of any changes to these water conditions should be investigated. For example, in many major cities around the world the ground water level is rising.



The site investigation should also establish the location of any services (gas, water, electricity, telecommunications, sewers andlor tunnels) that are in the vicinity of the proposed construction. The type (strip, raft andlor piled) and depth of the foundations of any adjacent buildings should also be determined. The allowable movements of these services and foundations should then be established.

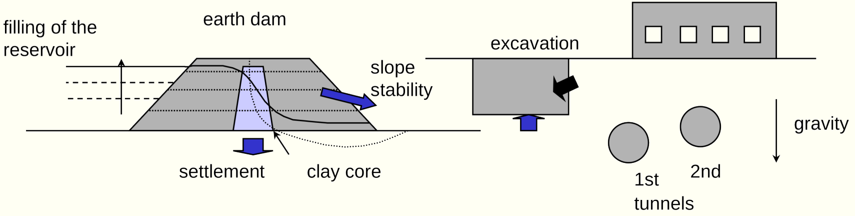
Any restrictions on the performance of the new geotechnical structure must be identified. Such restrictions can take many different forms. For example, due to the close proximity of adjacent services and structures there may be restrictions imposed on ground movements.



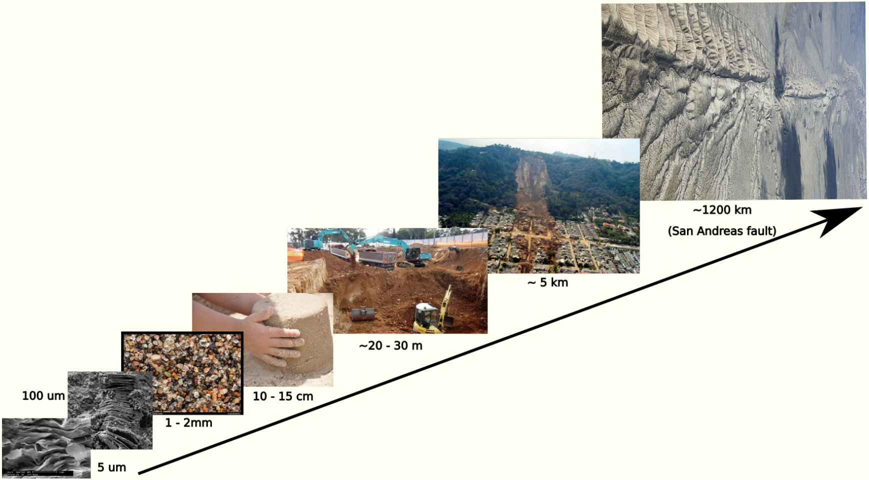
Once the above information has been collected, the design constraints on the geotechnical structure can be established. These should cover the construction period and the design life of the structure. This process also implicitly identifies which types of structure are and are not appropriate. For example, when designing an excavation, if there is a restriction on the movement of the retained ground, propped or anchored embedded retaining walls are likely to be more appropriate than gravity or reinforced earth walls. The design constraints also determine the type of design analysis that needs to be undertaken.

Geotechnical modeling: What should be modeled?

- Self weight effect of soils (This is why soil moves)
- Construction sequence (Complex geometry)
- Water movement (undrained, consolidation, drained)
- Insitu stresses (stiffness/strength depends on current stresses and stress history)
- Predict the ability of a design to withstand extreme loading conditions (you only have one chance)



Scales of modeling in geotechnical engineering



Soil behavior

- nonhomogeneous,
- anisotropic,
- non-linear,
- initial stress conditions,
- stress history
- Geometry - very complex

Soil Mechanics in practice - largely empirical

Advanced analysis in geotechnical engineering

Geotechnical design:

- Assess applied forces
- evaluate "performance" (stability & movements) under working and ultimate loads

Analysis:

- Mathematical framework to perform calculations for these quantities
- Requires idealization of: geometry, soil properties, and loading conditions
- Analysis is a tool in design, but design involves more: acceptable movements, constraints, site characterization, etc.

Advanced analysis in geotechnical engineering

Geotechnical design:

- Assess applied forces
- evaluate "performance" (stability & movements) under working and ultimate loads

Analysis:

- Mathematical framework to perform calculations for these quantities
- Requires idealization of: geometry, soil properties, and loading conditions
- Analysis is a tool in design, but design involves more: acceptable movements, constraints, site characterization, etc.

As part of the design process, it is necessary for an engineer to perform calculations to provide estimates of the above quantities. Analysis provides the mathematical framework for such calculations. A good analysis, which simulates real behaviour, allows the engineer to understand problems better. While an important part of the design process, analysis only provides the engineer with a tool to quantify effects once material properties and loading conditions have been set. The design process involves considerably more than analysis.

Classical vs advanced analysis

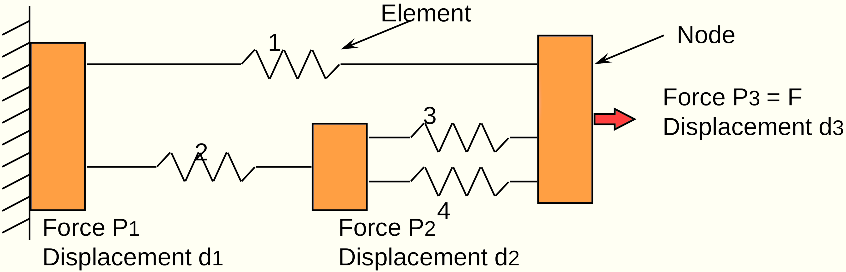
Classical approach:

- Failure estimates
  - rigid perfectly-plastic stress-strain assumptions
  - calculate factor of safety (What value do you pick?)
- Deformation estimates
  - Elastic analysis
  - Use average elastic properties (like what??)

Advanced analysis:

- Failure and deformation are obtained from the same analysis
- Handle complex geometry
- More difficult to perform, more computational requirements and more info on soil behavior $\sigma - \epsilon$
- Need to know how to do it right!

Matrix analysis of structures



- What are the known variables? $d_1 = 0, P_2 = 0, P_3 = F(\text{constant})$
- What are the unknowns? P_1, d_2, d_3
- What do we know? Force or distortion relations at an element level.

Matrix analysis of structures: Equilibrium

A structure is considered to be in equilibrium if, initially at rest, it remains at rest when subjected to a system of forces and couples. If a structure is in equilibrium, then all of its members and joints must also be in equilibrium.

- $P_1 = -S_1 - S_2$
- $P_2 = S_2 - S_3 - S_4$
- $P_3 = S_1 + S_3 + S_4$

$$\begin{bmatrix} P_1 \\ P_2 \\ P_3 \end{bmatrix} = \begin{bmatrix} -1 & -1 & 0 & 0 \\ 0 & 1 & -1 & -1 \\ 1 & 0 & 1 & 1 \end{bmatrix} \begin{bmatrix} S_1 \\ S_2 \\ S_3 \\ s_4 \end{bmatrix}$$

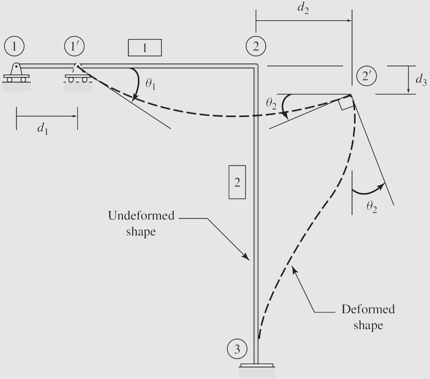
$$\mathbf{P} = \mathbf{A^T S}$$

Matrix analysis of structures: Compatibility

- compatibility relates the deformations of a structure so that its various parts (members, joints, and supports) fit together without any gaps or overlaps.
- ensure that the deformed shape of the structure is continuous (except at the locations of any internal hinges or rollers), and is consistent with the support conditions.

- compatibility relates the deformations of a structure so that its various parts (members, joints, and supports) fit together without any gaps or overlaps.
- ensure that the deformed shape of the structure is continuous (except at the locations of any internal hinges or rollers), and is consistent with the support conditions.

Deflection profile shown for a hinge is incompatible, because it can't be differentiated (the slope cannot be evaluated) at the hinge. Hence incompatible.



Matrix analysis of structures: Compatibility

v = internal spring distortion d = nodal displacement

- $v_1 = d_3 - d_1$
- $v_2 = d_2 - d_1$
- $v_3 = d_3 - d_2$
- $v_4 = d_3 - d_2$

$$\begin{bmatrix} v_1 \\ v_2 \\ v_3 \\ v_4 \end{bmatrix} = \begin{bmatrix} -1 & 0 & 1 \\ -1 & 1 & 0 \\ 0 & -1 & 1 \\ 0 & -1 & 1 \end{bmatrix} \begin{bmatrix} d_1 \\ d_2 \\ d_3 \end{bmatrix}$$

$$\mathbf{v} = \mathbf{A}\mathbf{d}$$

Force-distance relationship: spring constant

spring #	1	2	3	4
stiffness ($F.L^{-1}$)	3	2	1	2

$$\begin{bmatrix} S_1 \\ S_2 \\ S_3 \\ S_4 \end{bmatrix} = \begin{bmatrix} 3 & 0 & 0 & 0 \\ 0 & 2 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 2 \end{bmatrix} \begin{bmatrix} v_1 \\ v_2 \\ v_3 \\ v_4 \end{bmatrix}$$

$$\mathbf{s} = \mathbf{D}\mathbf{v}$$

Matrix analysis of structures: Direct Method

Combine all the equations: $\mathbf{P} = \mathbf{A^T S} = \mathbf{A^T D v} = \mathbf{A^T D A d} = \mathbf{K d}$
where $\mathbf{K} = A^T DA$ (Global stiffness matrix)

$$K = \begin{bmatrix} -1 & -1 & 0 & 0 \\ 0 & 1 & -1 & -1 \\ 1 & 0 & 1 & 1 \end{bmatrix} \begin{bmatrix} 3 & 0 & 0 & 0 \\ 0 & 2 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 2 \end{bmatrix} \begin{bmatrix} -1 & 0 & 1 \\ -1 & 1 & 0 \\ 0 & -1 & 1 \\ 0 & -1 & 1 \end{bmatrix}$$

$$= \begin{bmatrix} 5 & -2 & -3 \\ -2 & 5 & -3 \\ -3 & -3 & 6 \end{bmatrix}$$

$$\begin{bmatrix} P_1 \\ P_2 \\ P_3 \end{bmatrix} = \begin{bmatrix} 5 & -2 & -3 \\ -2 & 5 & -3 \\ -3 & -3 & 6 \end{bmatrix} \begin{bmatrix} d_1 \\ d_2 \\ d_3 \end{bmatrix}$$

Apply Boundary conditions $d_1 = 0$, $P_2 = 0$ and $P_3 = F$ and solve P_1, d_2 and d_3

Matrix analysis of structures: Direct Method

Combine all the equations: $\mathbf{P} = \mathbf{A^T S} = \mathbf{A^T D v} = \mathbf{A^T D A d} = \mathbf{K d}$
where $\mathbf{K} = A^T DA$ (Global stiffness matrix)

$$K = \begin{bmatrix} -1 & -1 & 0 & 0 \\ 0 & 1 & -1 & -1 \\ 1 & 0 & 1 & 1 \end{bmatrix} \begin{bmatrix} 3 & 0 & 0 & 0 \\ 0 & 2 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 2 \end{bmatrix} \begin{bmatrix} -1 & 0 & 1 \\ -1 & 1 & 0 \\ 0 & -1 & 1 \\ 0 & -1 & 1 \end{bmatrix}$$

$$= \begin{bmatrix} 5 & -2 & -3 \\ -2 & 5 & -3 \\ -3 & -3 & 6 \end{bmatrix}$$

$$\begin{bmatrix} P_1 \\ P_2 \\ P_3 \end{bmatrix} = \begin{bmatrix} 5 & -2 & -3 \\ -2 & 5 & -3 \\ -3 & -3 & 6 \end{bmatrix} \begin{bmatrix} d_1 \\ d_2 \\ d_3 \end{bmatrix}$$

Apply Boundary conditions $d_1 = 0$, $P_2 = 0$ and $P_3 = F$ and solve P_1, d_2 and d_3

Transpose of a linear mapping of two vectors of the same field (system), makes both $\mathbf{A}$ and $\mathbf{A}^T$ for forces and displacement relationships to have the same $\mathbf{A}$ matrix. $\mathbf{A}$ is used when relating nodal to internal variables, and $\mathbf{A}^T$ is used for the inverse relation. Note: $\mathbf{A}$ is a non-square matrix and is not invertible. $\mathbf{A}^T \neq \mathbf{A}^{-1}$

Matrix analysis of structures

known displacements and forces

↓

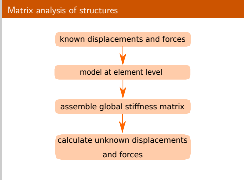
model at element level

↓

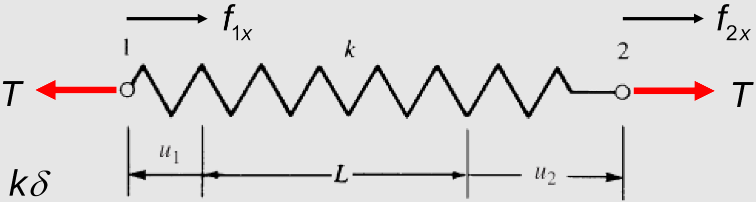
assemble global stiffness matrix

↓

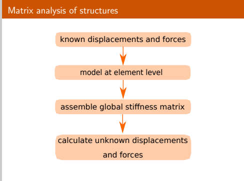
calculate unknown displacements and forces



Stiffness method: Tensile forces produce a total elongation (deformation) δ of the spring. For linear springs, the force T and the displacement u are related by Hooke's law. where deformation of the spring δ is given as: $\delta = u(L) - u(0) = u_2 - u_1$. Forces $f_{1x} = -T$ and $f_{2x} = T$.



$$T = k\delta$$



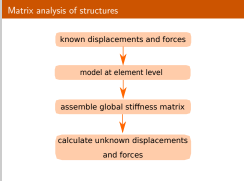
We can now derive the spring element stiffness matrix as follows. Rewrite the forces in terms of the nodal displacements:

$$T = -f_{1x} = k(u_2 - u_1) \rightarrow f_{1x} = k(u_1 - u_2)$$

$$T = f_{2x} = k(u_2 - u_1) \rightarrow f_{2x} = k(-u_1 + u_2)$$

We can write the last two force-displacement relationships in matrix form as:

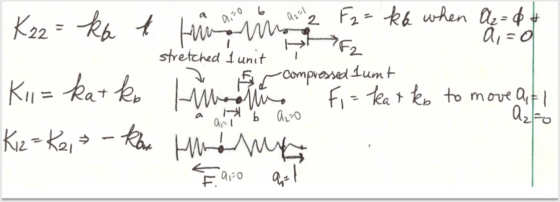
$$\begin{bmatrix} f_{1x} \\ f_{2x} \end{bmatrix} = \begin{bmatrix} k & -k \\ -k & k \end{bmatrix} \begin{bmatrix} u_1 \\ u_2 \end{bmatrix}$$



Stiffness method Force $F = K * a$. Where, K represents force at DOF given unit displacement at DOF.

$$\begin{bmatrix} F_1 \\ F_2 \end{bmatrix} = \begin{bmatrix} K_{11} & K_{12} \\ K_{21} & K_{22} \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \end{bmatrix}$$

K_{ij} is force at DOF i given unit displacement at DOF j with all other dof held constant.



$$K = \begin{bmatrix} k_a + k_b & -k_b \\ -k_b & k_b \end{bmatrix}$$

Governing equations in stress-deformation analysis

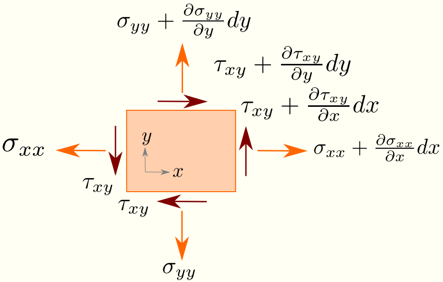
In stress-deformation analysis, we need to consider:

- **Equilibrium - static conditions**
  - forces and stress must agree across the region of interest. (geometric problem)
- **Compatibility-kinematic conditions**
  - geometry, displacement and strains must agree across the region of interest. (geometric problem)
- **Stress-strain relationship on physical conditions**
  - material dependent relationship between stress and strain must be specified. (element level)

Governing equations in stress-deformation analysis

The governing differential equation for equilibrium expresses: $\sum \mathbf{F} = m\mathbf{a}$

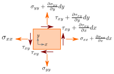
- σ_{xx} acting on face dy in the $-x$ direction
- τ_{xy} acting on face dx in the $-x$ direction
- $\sigma_{xx} + \frac{\partial \sigma_{xx}}{\partial x} dx$ acting on face dy in the $+x$ direction
- $\tau_{xy} + \frac{\partial \tau_{xy}}{\partial y} dy$ acting on face dx in the $+x$ direction
- Plus "body forces" due to gravity: $\rho f_x dx dy$ where f_x is body force per unit mass



Governing equations in stress-deformation analysis

The governing differential equation for equilibrium expresses: $\sum \mathbf{F} = m\mathbf{a}$

- σ_{xx} acting on face dy in the $-x$ direction
- τ_{xy} acting on face dx in the $-x$ direction
- $\sigma_{xx} + \frac{\partial \sigma_{xx}}{\partial x} dx$ acting on face dy in the $+x$ direction
- $\tau_{xy} + \frac{\partial \tau_{xy}}{\partial y} dy$ acting on face dx in the $+x$ direction
- Plus "body forces" due to gravity: $\rho f_x dxdy$ where f_x is body force per unit mass



σ_{xy}, the term x denotes the direction of the stress component acts on a cut normal to the x-axis (denotes the plane). The y denotes the direction of the stress component.

Frequently in the literature the axes are labelled 1, 2 & 3 rather than x, y & z.

Equilibrium equations

Summing all this in the x-direction gives:

$$-\sigma_{xx}dy - \tau_{xy}dx + \left(\sigma_{xx} + \frac{\partial\sigma_{xx}}{\partial x}dx\right)dy + \left(\tau_{xy} + \frac{\partial\tau_{xy}}{\partial y}dy\right)dx + \rho f_x dxdy = \rho dxdy a_x$$

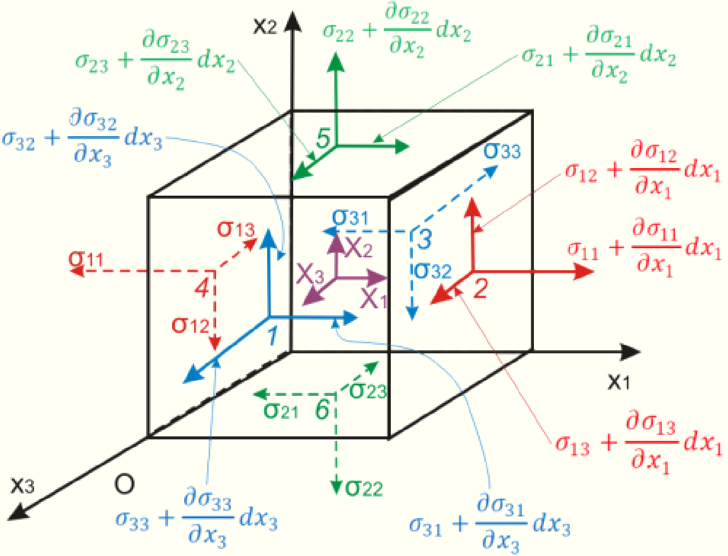
Cleaning up terms that cancel, and dividing through by *dxdy* gives

$$\frac{\partial\sigma_{xx}}{\partial x} + \frac{\partial\tau_{xy}}{\partial y} + \rho f_x = \rho a_x$$

And summing forces in the y-direction leads to:

$$\frac{\partial\sigma_{yy}}{\partial y} + \frac{\partial\tau_{xy}}{\partial x} + \rho f_y = \rho a_y$$

Equilibrium in 3D



Equilibrium in 3D

$$\frac{\partial \sigma_{xx}}{\partial x} + \frac{\partial \sigma_{xy}}{\partial y} + \frac{\partial \sigma_{xz}}{\partial z} + \rho f_x = \rho a_x$$
$$\frac{\partial \sigma_{yx}}{\partial x} + \frac{\partial \sigma_{yy}}{\partial y} + \frac{\partial \sigma_{yz}}{\partial z} + \rho f_y = \rho a_y$$
$$\frac{\partial \sigma_{zx}}{\partial x} + \frac{\partial \sigma_{zy}}{\partial y} + \frac{\partial \sigma_{zz}}{\partial z} + \rho f_z = \rho a_z$$

The governing differential equation for equilibrium expresses $\sum \mathbf{F} = m\mathbf{a}$ in terms of derivatives of the stress tensor as: $\nabla \cdot \boldsymbol{\sigma} + \rho \mathbf{f} = \rho \mathbf{a}$

$\boldsymbol{\sigma}$ is the stress tensor,

ρ is density,

$\mathbf{f}$ is the body force vector per unit mass and

$\mathbf{a}$ is the acceleration vector.

Stress equilibrium

If the object is in equilibrium, then $\mathbf{a} = 0$ and $\sum \mathbf{F} = 0$.

$$\frac{\partial \sigma_{xx}}{\partial x} + \frac{\partial \sigma_{xy}}{\partial y} + \frac{\partial \sigma_{xz}}{\partial z} + b_x = 0$$
$$\frac{\partial \sigma_{yx}}{\partial x} + \frac{\partial \sigma_{yy}}{\partial y} + \frac{\partial \sigma_{yz}}{\partial z} + b_y = 0$$
$$\frac{\partial \sigma_{zx}}{\partial x} + \frac{\partial \sigma_{zy}}{\partial y} + \frac{\partial \sigma_{zz}}{\partial z} + b_z = 0$$

Stresses: $[\sigma_{xx}, \sigma_{yy}, \sigma_{zz}, \sigma_{xy}, \sigma_{yz}, \sigma_{zx}]^T$.
Equilibrium equation: $\nabla^T \boldsymbol{\sigma} + \mathbf{b} = 0$
Then:

$$\nabla^T = \begin{bmatrix} \frac{\partial}{\partial x} & 0 & 0 & \frac{\partial}{\partial y} & 0 & \frac{\partial}{\partial z} \\ 0 & \frac{\partial}{\partial y} & 0 & \frac{\partial}{\partial x} & \frac{\partial}{\partial z} & 0 \\ 0 & 0 & \frac{\partial}{\partial z} & 0 & \frac{\partial}{\partial y} & \frac{\partial}{\partial x} \end{bmatrix}$$

Stress equilibrium

If the object is in equilibrium, then $\mathbf{a} = 0$ and $\sum \mathbf{F} = 0$.

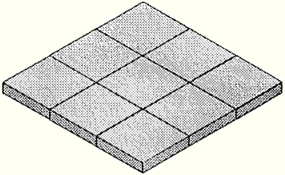
$$\frac{\partial \sigma_{xx}}{\partial x} + \frac{\partial \sigma_{xy}}{\partial y} + \frac{\partial \sigma_{xz}}{\partial z} + b_x = 0$$
$$\frac{\partial \sigma_{yx}}{\partial x} + \frac{\partial \sigma_{yy}}{\partial y} + \frac{\partial \sigma_{yz}}{\partial z} + b_y = 0$$
$$\frac{\partial \sigma_{zx}}{\partial x} + \frac{\partial \sigma_{zy}}{\partial y} + \frac{\partial \sigma_{zz}}{\partial z} + b_z = 0$$

Stresses: $[\sigma_{xx}, \sigma_{yy}, \sigma_{zz}, \sigma_{xy}, \sigma_{yz}, \sigma_{zx}]^T$.
Equilibrium equation: $\nabla^T \boldsymbol{\sigma} + \mathbf{b} = 0$
Then:

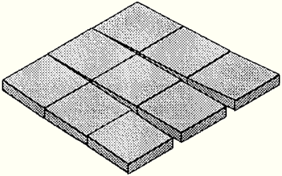
$$\nabla^T = \begin{bmatrix} \frac{\partial}{\partial x} & 0 & 0 & \frac{\partial}{\partial y} & 0 & \frac{\partial}{\partial z} \\ 0 & \frac{\partial}{\partial y} & 0 & \frac{\partial}{\partial x} & \frac{\partial}{\partial z} & 0 \\ 0 & 0 & \frac{\partial}{\partial z} & 0 & \frac{\partial}{\partial y} & \frac{\partial}{\partial x} \end{bmatrix}$$

Divergence is a vector operator that produces a scalar field, giving the quantity of a vector field's source at each point. In physical terms, the extent to which there is more of some quantity exiting an infinitesimal region of space than entering it. If the divergence is nonzero at some point then there is compression or expansion at that point.

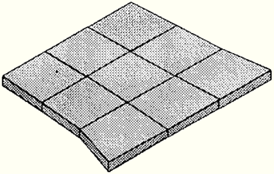
Governing equations: Compatibility



(a) original



(b) non-compatible



(c) compatible

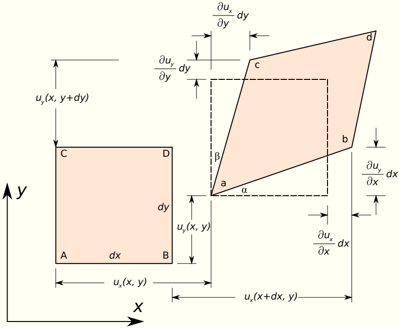
Governing equations: Displacement - strain relationship

Displacement - strain relationship: $\boldsymbol{\varepsilon} = \nabla \mathbf{u}$
Where,

$$\varepsilon_{xx} = \frac{\partial u_x}{\partial x}$$

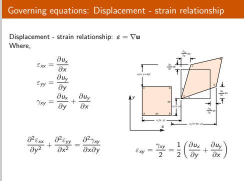
$$\varepsilon_{yy} = \frac{\partial u_y}{\partial y}$$

$$\gamma_{xy} = \frac{\partial u_x}{\partial y} + \frac{\partial u_y}{\partial x}$$



$$\frac{\partial^2 \varepsilon_{xx}}{\partial y^2} + \frac{\partial^2 \varepsilon_{yy}}{\partial x^2} = \frac{\partial^2 \gamma_{xy}}{\partial x \partial y}$$

$$\varepsilon_{xy} = \frac{\gamma_{xy}}{2} = \frac{1}{2}\left(\frac{\partial u_x}{\partial y} + \frac{\partial u_y}{\partial x}\right)$$



Compatibility in 3D

$$
\begin{aligned}
\frac{\partial^2 \varepsilon_{yy}}{\partial z^2} + \frac{\partial^2 \varepsilon_{zz}}{\partial y^2} &= 2\frac{\partial^2 \varepsilon_{yz}}{\partial y \partial z}, &\quad \frac{\partial^2 \varepsilon_{xx}}{\partial y \partial z} &= \frac{\partial}{\partial x}\left(-\frac{\partial \varepsilon_{yz}}{\partial x} + \frac{\partial \varepsilon_{zx}}{\partial y} + \frac{\partial \varepsilon_{xy}}{\partial z}\right) \\
\frac{\partial^2 \varepsilon_{zz}}{\partial x^2} + \frac{\partial^2 \varepsilon_{xx}}{\partial z^2} &= 2\frac{\partial^2 \varepsilon_{zx}}{\partial z \partial x}, &\quad \frac{\partial^2 \varepsilon_{yy}}{\partial z \partial x} &= \frac{\partial}{\partial y}\left(+\frac{\partial \varepsilon_{yz}}{\partial x} - \frac{\partial \varepsilon_{zx}}{\partial y} + \frac{\partial \varepsilon_{xy}}{\partial z}\right) \\
\frac{\partial^2 \varepsilon_{xx}}{\partial y^2} + \frac{\partial^2 \varepsilon_{yy}}{\partial x^2} &= 2\frac{\partial^2 \varepsilon_{xy}}{\partial x \partial y}, &\quad \frac{\partial^2 \varepsilon_{zz}}{\partial x \partial y} &= \frac{\partial}{\partial z}\left(+\frac{\partial \varepsilon_{yz}}{\partial x} + \frac{\partial \varepsilon_{zx}}{\partial y} - \frac{\partial \varepsilon_{xy}}{\partial z}\right)
\end{aligned}
$$

Equilibrium and compatibility conditions

Combining the Equilibrium and Compatibility conditions gives:

- Unknowns: 6 stresses + 6 strains + 3 displacements = 15
- Equations: 3 equilibrium + 6 compatibility = 9

To obtain a solution therefore requires 6 more equations. These come from the constitutive relationships

Governing equations: Stress-strain relationship

Stress - strain relationship: $\boldsymbol{\sigma} = \mathbf{D}\boldsymbol{\varepsilon}$

$$\begin{bmatrix} \sigma_{xx} \\ \sigma_{yy} \\ \sigma_{zz} \\ \sigma_{xy} \\ \sigma_{yz} \\ \sigma_{zx} \end{bmatrix} = \begin{bmatrix} D_{xxxx} & D_{xxyy} & D_{xxzz} & D_{xxxy} & D_{xxyz} & D_{xxzx} \\ D_{yyxx} & D_{yyyy} & D_{yyzz} & D_{yyxy} & D_{yyyz} & D_{yyzx} \\ D_{zzxx} & D_{zzyy} & D_{zzzz} & D_{zzxy} & D_{zzyz} & D_{zzzx} \\ D_{xyxx} & D_{xyyy} & D_{xyzz} & D_{xyxy} & D_{xyyz} & D_{xyzx} \\ D_{yzxx} & D_{yzyy} & D_{yzzz} & D_{yzxy} & D_{yzyz} & D_{yzzx} \\ D_{zxxx} & D_{zxyy} & D_{zxzz} & D_{zxxy} & D_{zxyz} & D_{zxzx} \end{bmatrix} \begin{bmatrix} \varepsilon_{xx} \\ \varepsilon_{yy} \\ \varepsilon_{zz} \\ \varepsilon_{xy} \\ \varepsilon_{yz} \\ \varepsilon_{zx} \end{bmatrix}$$

Governing equations in stress-deformation analysis

What are the variables used in the governing equations?

1. displacements $\mathbf{u}$ in the body
2. strains ε in the body or within the elements
3. stresses $\boldsymbol{\sigma}$ in the body or within the elements

Advanced analysis involves:

1. Equilibrium: External forces + internal stresses agree
2. Compatibility: Displacements fields agree (no gaps) + strains (derivatives)
3. Stress-strain relationship (constitutive behaviour)

Governing equations in stress-deformation analysis

What are the variables used in the governing equations?

- displacements **u** in the body
- strains ε in the body or within the elements
- stresses $\boldsymbol{\sigma}$ in the body or within the elements

Advanced analysis involves:

- Equilibrium: External forces + internal stresses agree
- Compatibility: Displacements fields agree (no gaps) + strains (derivatives)
- Stress-strain relationship (constitutive behaviour)

Lower and upper bound theorems: The exact determination of loads involved in the plastic deformation requires simultaneous solution of three sets of conditions:

1. equations of equilibrium
2. equations of compatibility
3. appropriate consitutive criteria (yield condition and flow rule)

Exact dertermination is often not easy, may be appropriate for simple shapes, but other cases we may have to use *numerical method*.

Governing equations in stress-deformation analysis

What are the variables used in the governing equations?
- displacements $\mathbf{u}$ in the body
- strains ε in the body or within the elements
- stresses $\boldsymbol{\sigma}$ in the body or within the elements

Advanced analysis involves:
- Equilibrium: External forces + internal stresses agree
- Compatibility: Displacements fields agree (no gaps) + strains (derivatives)
- Stress-strain relationship (constitutive behaviour)

Lower bound theorem: Any applied load is less than the actual limiting load, i.e., they will not cause collapse.
In rigid-plastic continua ther can be no plastic deformation under loads for which a stress distribution can be found that:

1. satisfies equilibrium everywhere
2. balances the externally applied loads, and
3. is everywhere within the yield locus.

Relax compatibility.

Governing equations in stress-deformation analysis

What are the variables used in the governing equations?

- displacements $\mathbf{u}$ in the body
- strains ε in the body or within the elements
- stresses $\boldsymbol{\sigma}$ in the body or within the elements

Advanced analysis involves:

- Equilibrium: External forces + internal stresses agree
- Compatibility: Displacements fields agree (no gaps) + strains (derivatives)
- Stress-strain relationship (constitutive behaviour)

Upper bound theorem: Apply enough load to acheive the desired change in component shape, e.g., process machinery
In rigid-plastic continua, plastic deformation must occur for any system of load calculated by equating the external work done by loads to the internal plastic work calcuated from a distribution of strain increments that:

1. satisfies the boundary displacement conditions, and
2. do not infringe incompressibility.

Relax equilibrium

What are the variables used in the governing equations?

- displacements $\mathbf{u}$ in the body
- strains ε in the body or within the elements
- stresses $\boldsymbol{\sigma}$ in the body or within the elements

Advanced analysis involves:

- Equilibrium: External forces + internal stresses agree
- Compatibility: Displacements fields agree (no gaps) + strains (derivatives)
- Stress-strain relationship (constitutive behaviour)

Limit equilibrium In this method of analysis an 'arbitrary' failure surface is adopted (assumed) and equilibrium conditions are considered for the failing soil mass, assuming that the failure criterion holds everywhere along the failure surface. The failure surface may be planar, curved or some combination of these. Only the global equilibrium of the 'blocks' of soil between the failure surfaces and the boundaries of the problem are considered. The internal stress distribution within the blocks of soil is not considered. Coulomb's wedge analysis and the method of slices are examples of limit equilibrium calculations.

Only a global equilibrium, rather than the local equilibirium of every point in the soil, is satisified.

Governing equations in stress-deformation analysis

What are the variables used in the governing equations?

- displacements $\mathbf{u}$ in the body
- strains ε in the body or within the elements
- stresses $\boldsymbol{\sigma}$ in the body or within the elements

Advanced analysis involves:

- Equilibrium: External forces + internal stresses agree
- Compatibility: Displacements fields agree (no gaps) + strains (derivatives)
- Stress-strain relationship (constitutive behaviour)

Method of analysis	**Solution requirements**				
	Equilibrium	**Compatibility**	**Constitutive law**	**Force**	**Disp**
Closed form	✓	✓	Linear elastic	✓	✓
Limit equilibrium	✓	×	Rigid with a failure criterion	✓	×
Lower bound	✓	×	Plasticity + flow-rule	✓	×
Upper bound	×	✓	Platicity + flow-rule	×	✓
Numerical analysis	✓	✓	Any	✓	✓