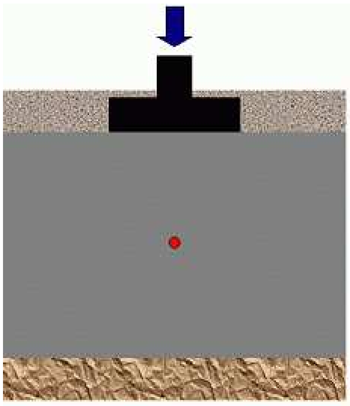
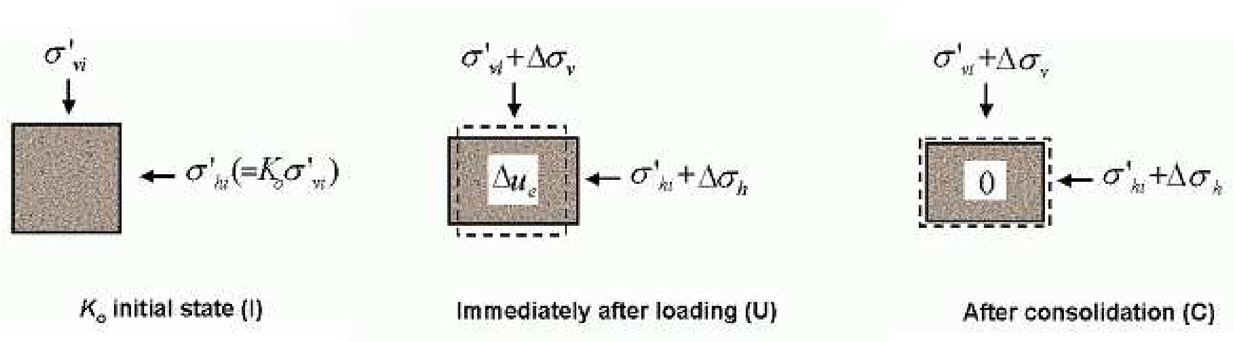
● **Stress path method** (Lambe 1964, 1967)

- Settlement estimation based on realistic deformation characteristics measured from stress path tests which **duplicate field stress paths and probable deformation modes** of soil elements.

- A rational experimental approach to more exact estimation of field settlement.

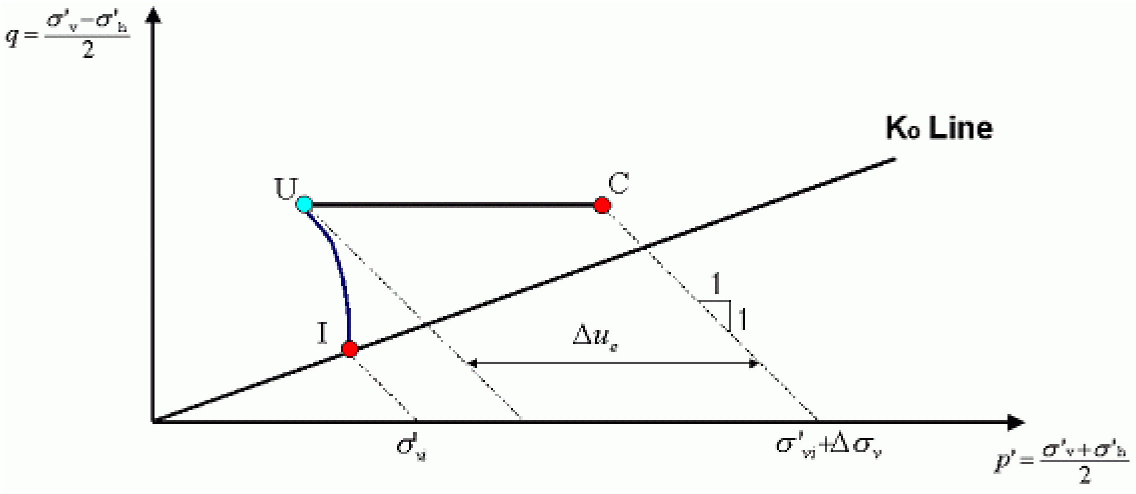
-Typical stress path of saturated clay deposits under foundation loading





→ Not K_o stress condition $\Delta\sigma_h \neq K_o\Delta\sigma_v$

→ Not 1D deformation mode $\varepsilon_h \neq 0$ (lateral strain occurs)



*** Stress state in p'-q diagram**

I : K_0 initial state

$$\left(\frac{\sigma'_{vi}+\sigma'_{hi}}{2}, \frac{\sigma'_{vi}-\sigma'_{hi}}{2}\right)$$

U : Immediately after loading

$$\left(\frac{\sigma'_{vi}+\sigma'_{hi}}{2}+\frac{\Delta\sigma_v+\Delta\sigma_h}{2}-\Delta u_e, \frac{\sigma'_{vi}-\sigma'_{hi}}{2}+\frac{\Delta\sigma_v-\Delta\sigma_h}{2}\right)$$

C : After consolidation

$$\left(\frac{\sigma'_{vi}+\sigma'_{hi}}{2}+\frac{\Delta\sigma_v+\Delta\sigma_h}{2}, \frac{\sigma'_{vi}-\sigma'_{hi}}{2}+\frac{\Delta\sigma_v-\Delta\sigma_h}{2}\right)$$

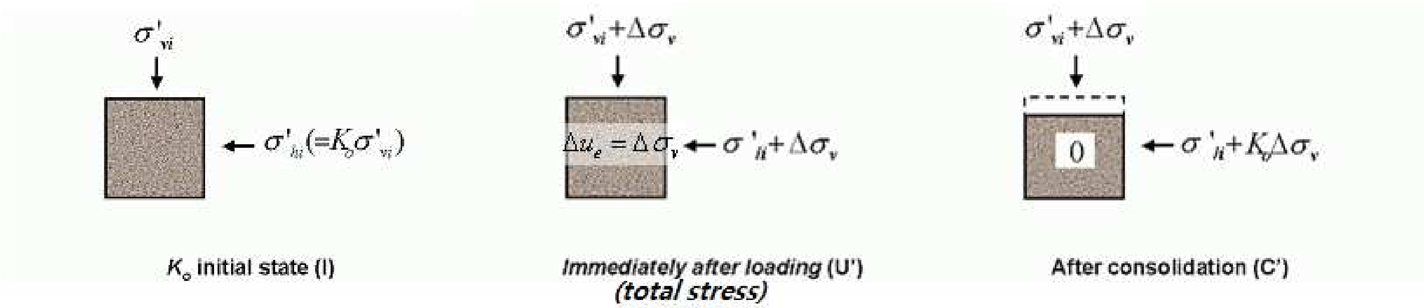
IU : Undrained path

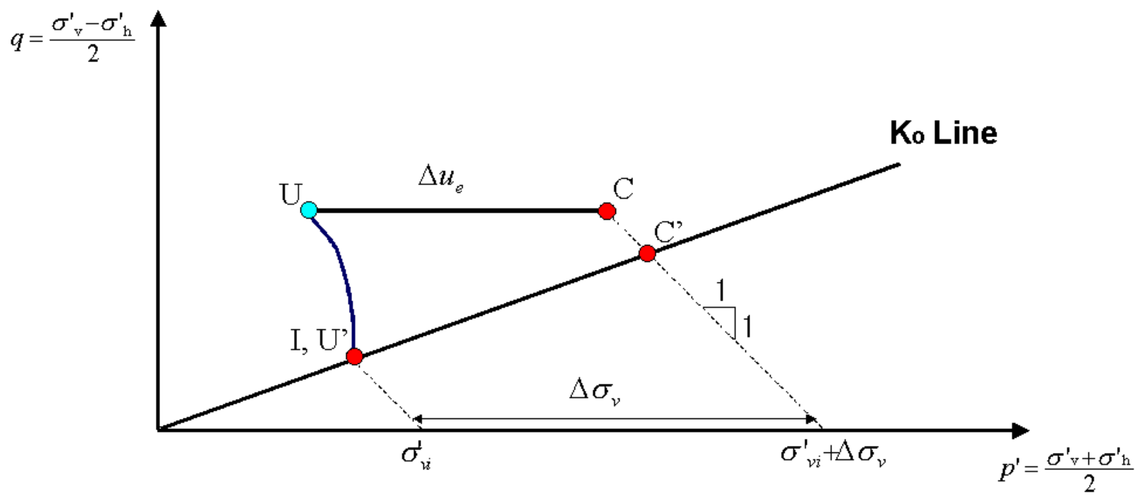
→ immediate strain (ε_{vu}) → immediate settlement (S_i)

UC : Consolidation path

→ consolidation strain (ε_{vc}) → consolidation settlement (S_c)

- 1D oedometer test





U'C' : Consolidation path of oedometer test.

→ 1D consolidation strain (ε_{vc-1D}) with no lateral strain

→ 1D consolidation settlement (S_{c-1D})

- Skempton and Bjerrum modification

→ 1D deformation mode of oedometer test

→ Governing stress increment : not $\Delta\sigma_v$ but Δu_e.

→ S&B consolidation strain : $\varepsilon_{vc-SB}=\varepsilon_{vc-1D}\times\frac{\Delta u_e}{\Delta\sigma_v}$

→ S&B consolidation settlement (S_{c-SB})

- Methods that are commonly used to predict field settlement ($S_t = S_i + S_c$)

  ① 1D consolidation settlement (S_{c-1D}).

  ② Immediate settlement + 1D consolidation settlement ($S_i + S_{c-1D}$).

  (Not correct theoretically)

  ③ Immediate settlement + S & B consolidation settlement ($S_i + S_{c-SB}$).

  ⇒ Unrealistic K_o stress path and 1D deformation mode are assumed.

  ⇒ Can be expected to give an erratic approximation of field settlement

- Stress path method

  - Lambe (1964, 1967)

  - Settlement estimation based on realistic deformation characteristics measured from stress path tests which duplicate field stress paths and probable deformation modes of soil elements.

  - A rational experimental approach to more exact estimation of field settlement.

i) Procedures

For a given structure,

① Divide subsoils into several layers and select average point of each layer.

② Determine field stress paths of the average points.

→ K_0 initial state (σ'_{vi} , σ'_{hi}).

→ Stress increment ($\Delta\sigma_v$, $\Delta\sigma_h$) ⇔ the elastic theory.

③ Duplicate the field stress paths in the laboratory.

→ Undisturbed samples.

→ TX tests for axisymmetric deformation mode (circular or square footing).

→ PS tests for plane strain deformation mode (strip footing, embankment).

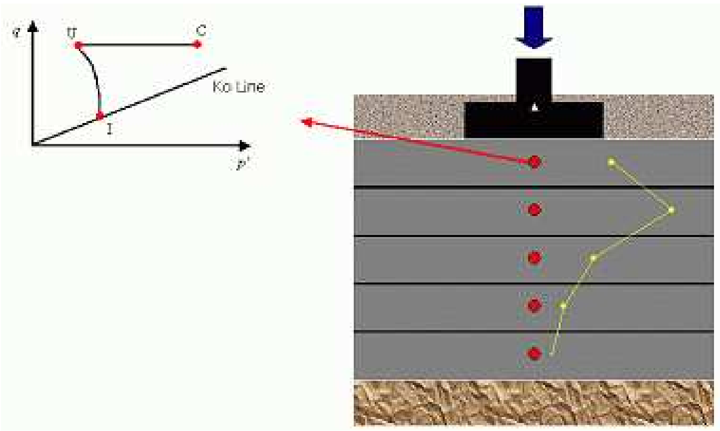
→ Measure vertical strains (ε_{vu} , ε_{vc}).

Instantaneous loading → possibility to break soil structure.
(misleading deformation mode)
but providing ε_{vu} and ε_{vc} , separately.

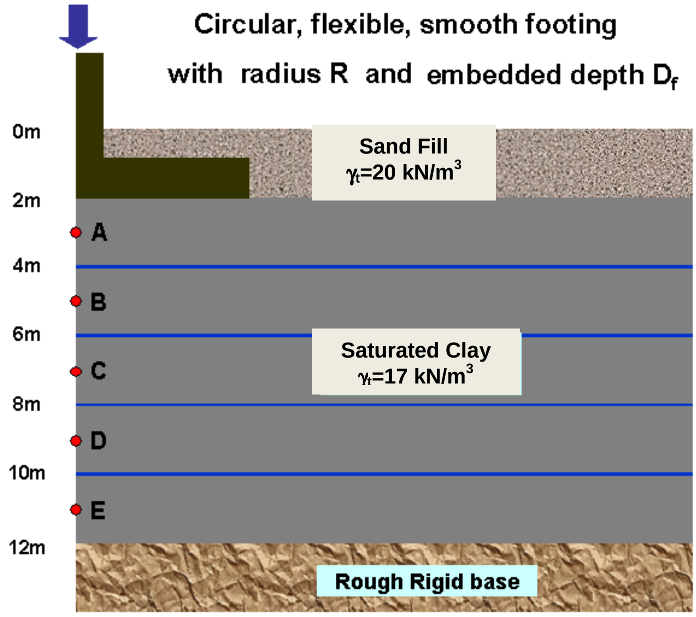
Stress rate loading → not breaking soil structure.
but not providing ε_{vu} and ε_{vc} , separately.

④ Estimate settlements by integrating the vertical strains with depth.

$$S_i = \int \varepsilon_{vu} dz = \sum \varepsilon_{vu} \Delta z \qquad S_c = \int \varepsilon_{vc} dz = \sum \varepsilon_{vc} \Delta z \qquad S_t = S_i + S_c$$



ii) Application example



(Q_{net} =135t, R=5m, D_f=2m)

Kaolinite,
NC state
w_n=37.6~40.2
C_c=0.253~0.286
C_r=0.110~0.126

① Divide subsoils into several layers and select average point of each layer.

② Determine field stress paths of the average points.

	Initial state		Stress increments		
	σ'_{vi} (kPa)	σ'_{hi} (kPa)	$\Delta\sigma_v$ (kPa)	$\Delta\sigma_h$ (kPa)	$\Delta\sigma_v - \Delta\sigma_h$ (kPa)
A	47.20	23.60	16.86	10.03	6.83
B	61.60	30.80	15.19	4.30	10.89
C	76.00	38.00	12.24	2.40	9.84
D	90.40	45.20	9.89	2.74	7.51
E	104.80	52.40	8.14	4.83	3.31

③ Duplicate the field stress paths in the laboratory (stress path test).

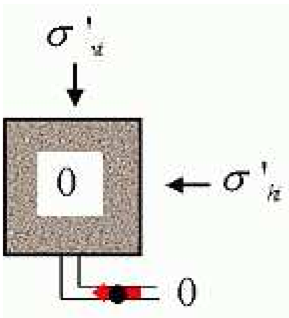
- 1st step : back pressure saturation → saturation of test specimen.

- 2nd step : K_0 consolidation → duplication of initial state (I).

  → Slowly increase vertical stress up to σ'_{vi} with $\varepsilon_h = 0$ condition by controlling cell pressure

  or

  → Slowly Increase vertical and horizontal stresses up to σ'_{vi} and $\sigma'_h = K_0 \sigma'_{vi}$.

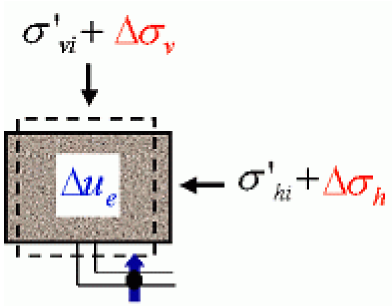


- 3rd step : undrained loading → duplication of undrained path (IU).

  → Increase vertical and horizontal stresses by $\Delta\sigma_v$ and $\Delta\sigma_h$ under undrained condition.

  How to increase?
  (stress control (what rate), step loading)

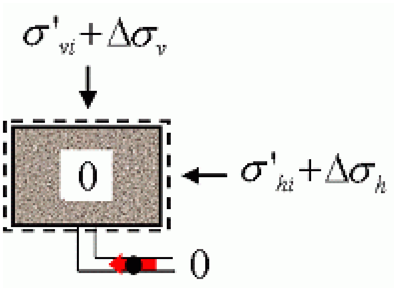
  → Measure immediate strains ε_{vu}, ε_{hu} and excess pore pressure Δu_e.



- 4th step : consolidation → duplication of consolidation path (UC).

→ Dissipate Δu_e by opening drainage value.

→ Measure consolidation strains ε_{vc} and ε_{hc} .



- Test results

	ε_{vu} (%)	ε_{hu} (%)	Δu_e (kPa)	ε_{vc} (%)	ε_{hc} (%)	ε_{vt} (%)	ε_{ht} (%)
A	1.118	-0.559	13.70	0.428	0.252	1.546	-0.307
B	3.465	-1.733	13.75	0.317	0.175	3.782	-1.558
C	0.771	-0.386	6.85	0.123	0.070	0.894	-0.316
D	0.286	-0.143	4.84	0.092	0.045	0.378	-0.098
E	0.088	-0.044	5.55	0.099	0.053	0.187	0.009

④ Estimate settlements by integrating the vertical strains with depth.

$S_i = \int \varepsilon_{vu} dz$ = (1.118+3.465+0.771+0.286+0.088)/100×2000 = 114.56mm

$S_c = \int \varepsilon_{vc} dz$ = (0.428+0.317+0.123+0.092+0.099)/100×2000 = 21.18mm

$S_t = S_i + S_c$ = 135.74mm

iii) Comparison with conventional methods

	Stress path method			Oedometer	S&B
	ε_{vu} (%)	ε_{vc} (%)	ε_{vt} (%)	ε_{vc-1D} (%)	ε_{vc-SB} (%)
A	1.118	0.428	1.546	1.292	1.050
B	3.465	0.317	3.782	0.877	0.794
C	0.771	0.123	0.894	0.548	0.307
D	0.286	0.092	0.378	0.367	0.180
E	0.088	0.099	0.187	0.259	0.177
	S_i =114.56mm	S_c =21.18mm	S_t =135.4mm	S_{c-1D} =66.86mm	S_{c-SB} =50.16mm

↑

(very closely related to the increment of loading (or loading rate))

If field conditions are far from being 1D,

- $S_{c-1D} < S_t$ ← Based on total settlement

  $\therefore$ S_{c-1D} → Underestimation of field total settlement.

- $S_{c-1D} > S_{c-SB} > S_c$ ← Based on consolidation settlement

  $\therefore$ $S_i + S_{c-1D}$ → Overestimation of field total settlement.

  $\therefore$ $S_i + S_{c-SB}$ → Overestimation of field total settlement.

  → But closer to field total settlement than $S_i + S_{c-1D}$.

iv) Limitations of stress path method

① Applicability of the elastic theory.

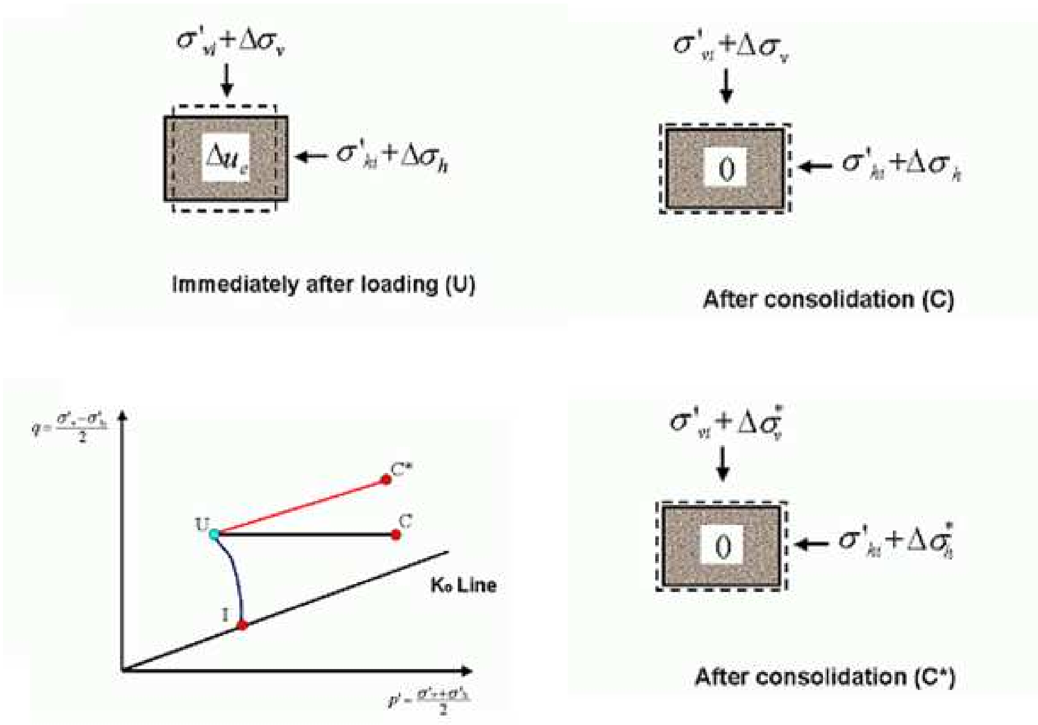
- Soils do not behave as linear elastic materials.
- $\Delta\sigma_v$ and $\Delta\sigma_h$ estimated based on the elastic theory may be erratic.

→ Overestimation of $\Delta\sigma_v$ and high underestimation of $\Delta\sigma_h$

→ Harr (1977) proposed an alternative approach using probabilistic theory.

→ However, no other way

② Change of stress increments during consolidation.



- Decrease of Poisson's ratio ($\nu_u = 0.5 \rightarrow \nu_d = 0.1 \sim 0.4$) → Decrease of $\Delta\sigma_h$
- Realistic inclined consolidation path UC* can not be duplicated using the conventional stress path testing scheme. (Why?)

● An efficient stress path testing scheme was newly devised by Kim (2004).

→ Back pressure equalization followed by actively-controlled consolidation.

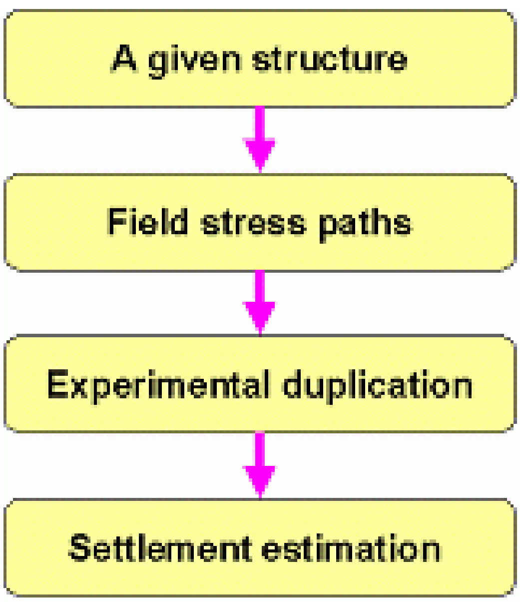
→ Any arbitrary consolidation path can be duplicated.

→ Exact Deformations of a tested consolidation path can be continuously measured by stress controlled test under drained condition. (One path by One test)

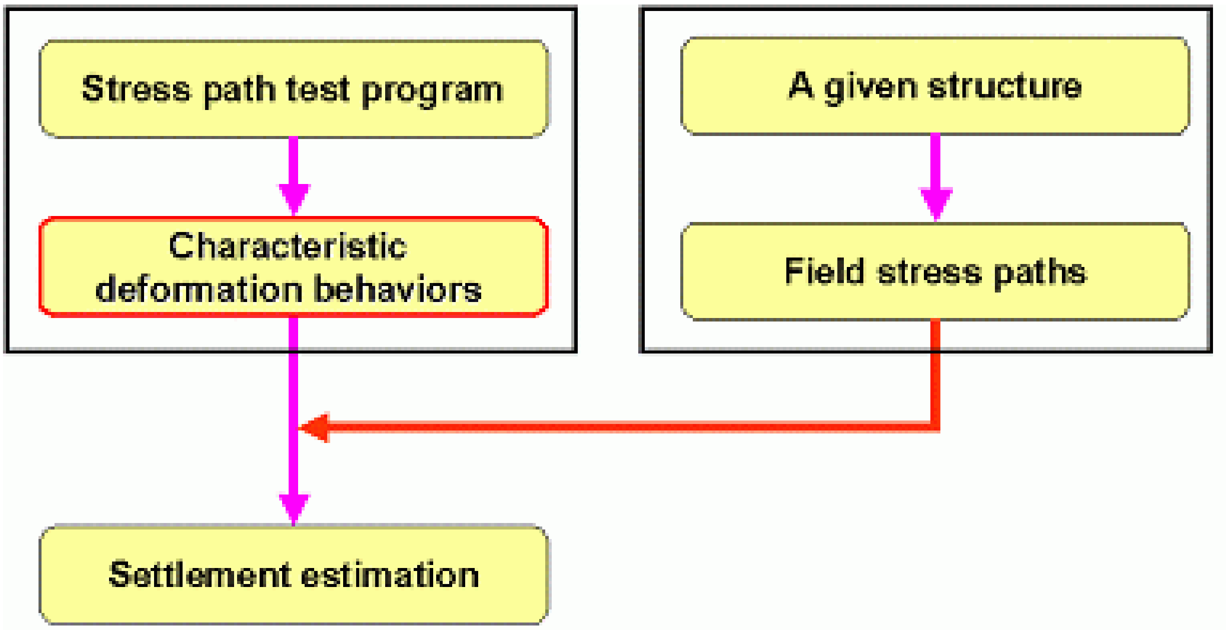
③ Too excessive experimental work.

- A number of laborious tests are required for every structure.
- Different types of structures require mostly different series of tests.
- Various design alternatives can not be easily examined.
- Modification of design factors during construction can not be readily reflected.

*** Conventional Stress Path Method**



- A more practical approach of stress path method was proposed by Kim (2004).



→ Characteristic behaviors of deformation which can cover all probable field stress paths are evaluated in advance by an economically-designed experimental program.

→ Settlements of various structures or design alternatives can be routinely estimated without additional tests by simply substituting their corresponding field stress paths into the characteristic behaviors.

→ Practicality of the proposed approach was maximized in the manner of minimizing experimental effort required to establish the characteristic behaviors of deformation.

** Effect of initial effective state → can be solved by employing normalized engineering properties concept.*