International Symposium
« Qualification of dynamic analyses of dams and their equipments and of probabilistic assessment seismic hazard in Europe », 31th August – 2nd September 2016 – Saint-Malo

Session 3 :

Soils properties and simplified analysis

A new simplified seismic stability analysis taking into account degradation of soil undrained stress-strain properties and effects of compaction

●Antoine Duttine, Fumio Tatsuoka, Taiki Shinbo, Yoshiyuki Mohri

Integrated Geotechnology Institute Limited 株式会社 複合技術研究所

National Institute of Technology, Ishikawa College 石川工業高等専門学校

茨城大学 Ibaraki University

SUMMARY

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JCOLD

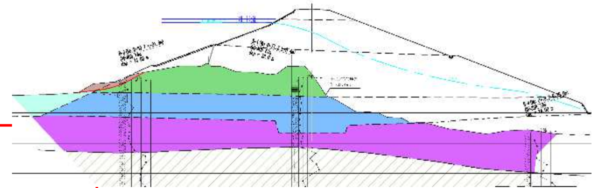
- Following the 2011 Great East Japan Earthquake, in the three prefectures of Iwate, Miyagi & Fukushima, around 15% of earth fill dams were significantly damaged (1951 out of 12500)

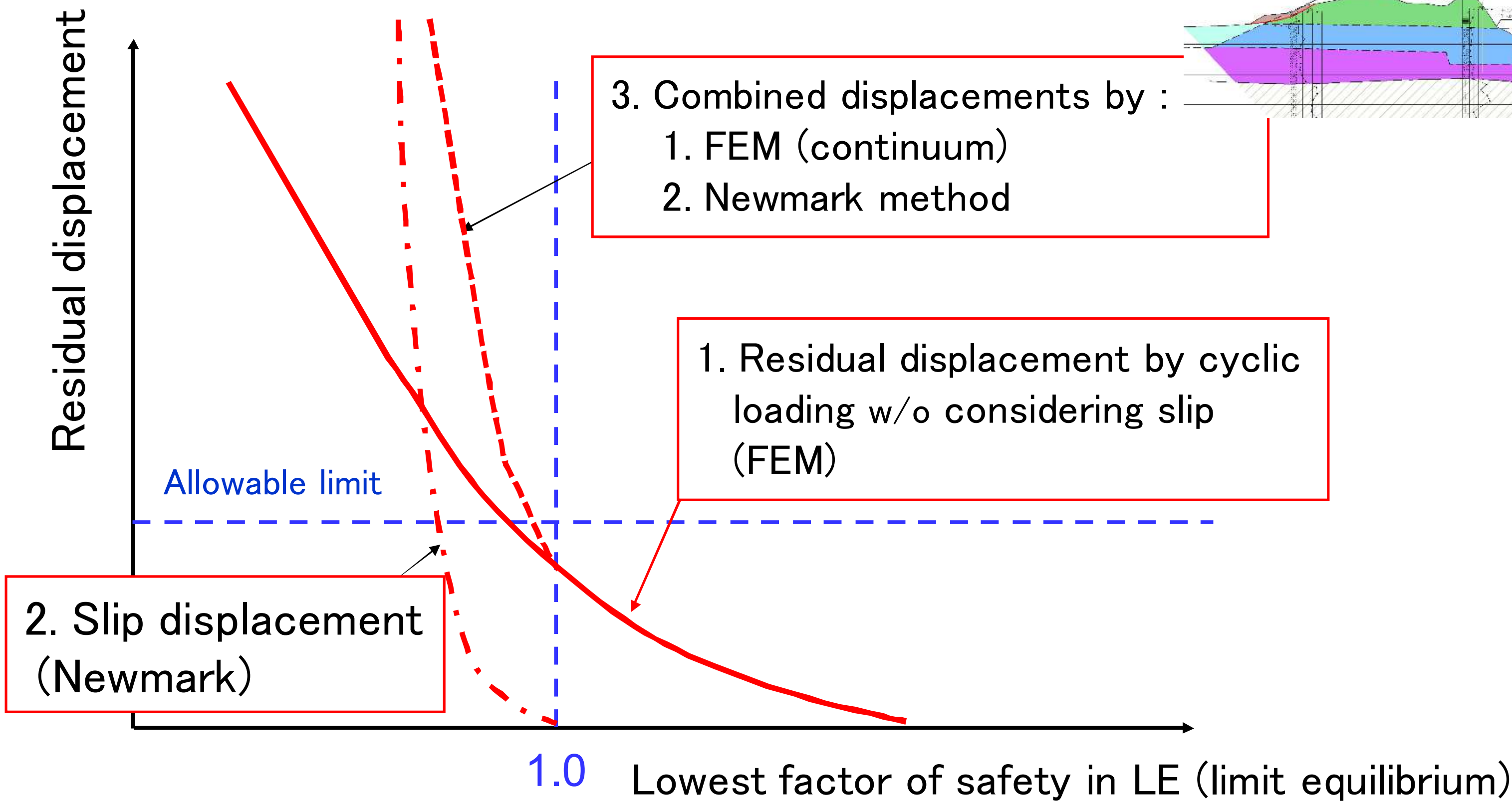
- Current seismic design analysis (LE, kh=0.15, F_s>1.2) can not explain Fujinuma dam failure and this 15% damage ratio. Besides, around 200,000earth-fill dams in japan!!

- Need for a simplified practical seismic analysis for high seismic loads: combination of FEM & Newmark

Fujinuma dam failure

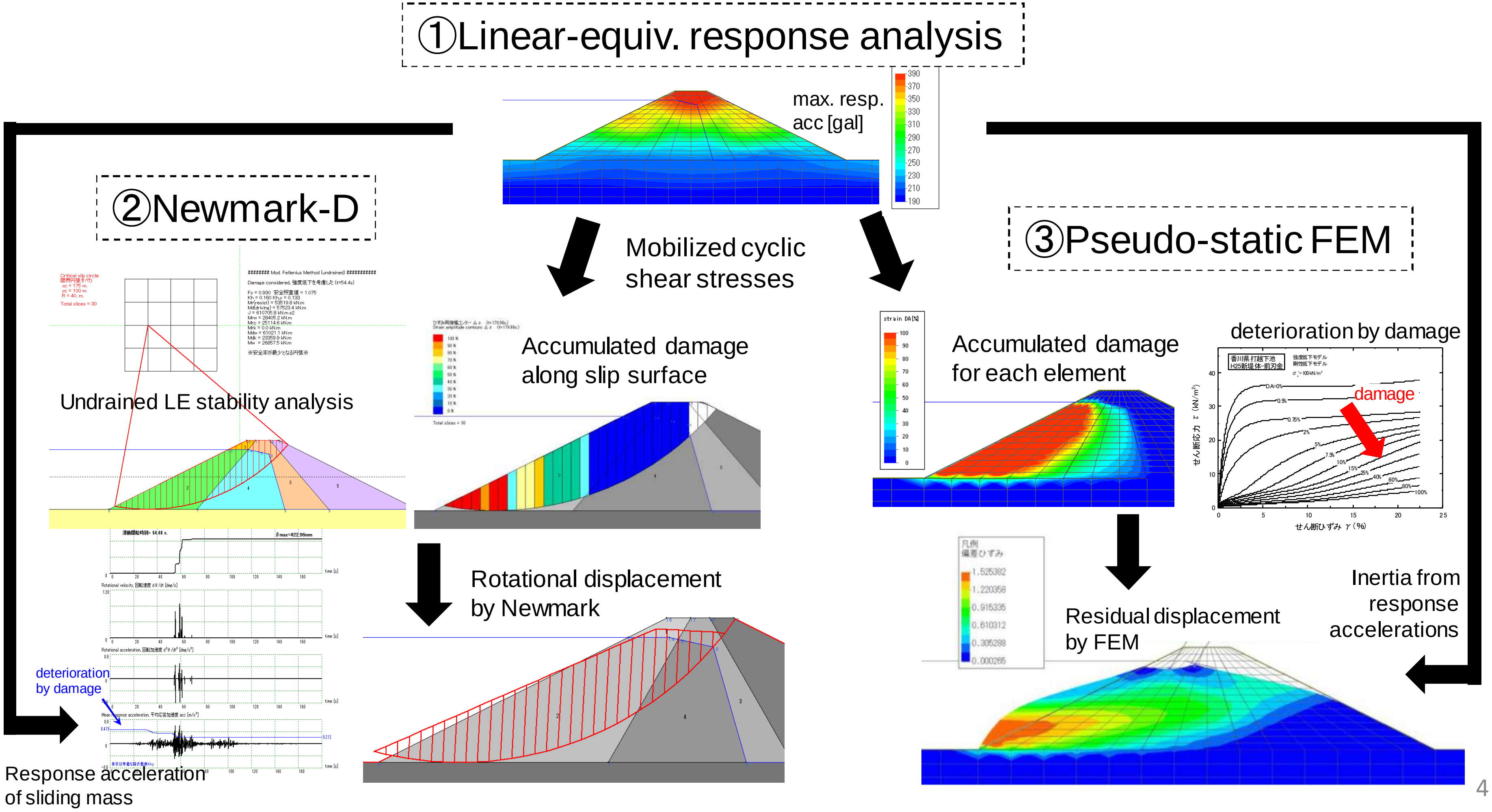
(H= 18.5m L= 133.2m, top fill composed of poorly compacted weak sandy soils, i.e. prone to strength degradation & liquefaction)





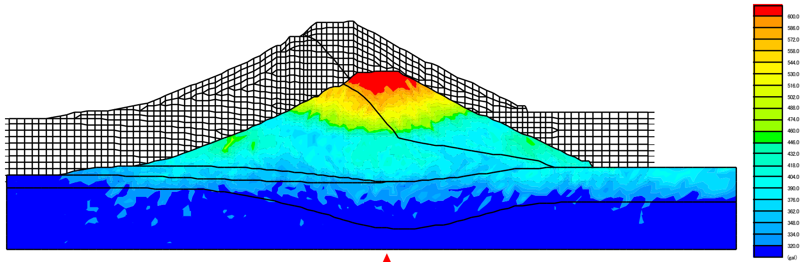
⇨ Crucial need to take into account in a simple way the degradation of soil rigidity and strength by seismic loading i.e. undrained cyclic loading (CL)

⇨ Development of modified Newmark method and pseudo-static FEM analyses in a united framework (cumulative damage and total stress concepts) along with relevant undrained cyclic+monotonic loading tests



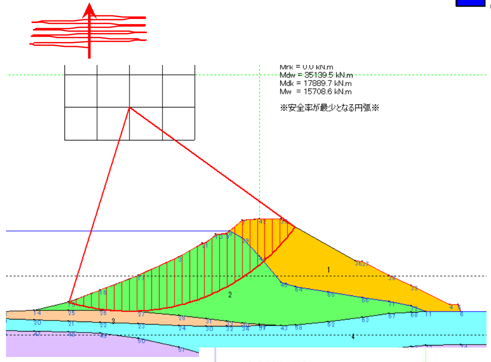
Procedure of Newmark-D analysis

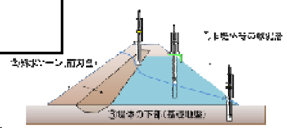
①Plane strain FEM dynamic response analysis （equivalent linear or non-linear analysis, not taking into account the degradation of stiffness by undrained CL and shear banding）



⇩

②Quasi-static LE stability analysis by Fellenius slice method（using undrained strength with saturated soil) to find the critical failure plane





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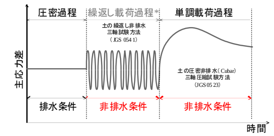
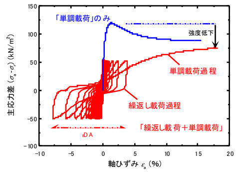
③Estimation of undrained strength degradation due to undrained CL by the cumulative damage concept based on uniform undrained CL & ML test results





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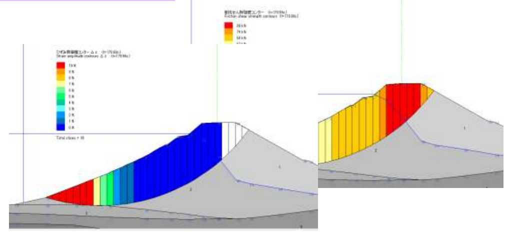
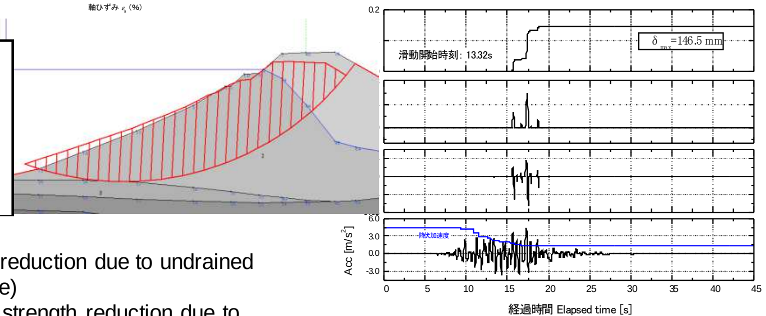
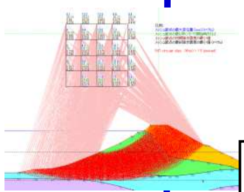
④Calculation of slip displacement for a given seismic motion by the Newmark-D method using degrading shear strength





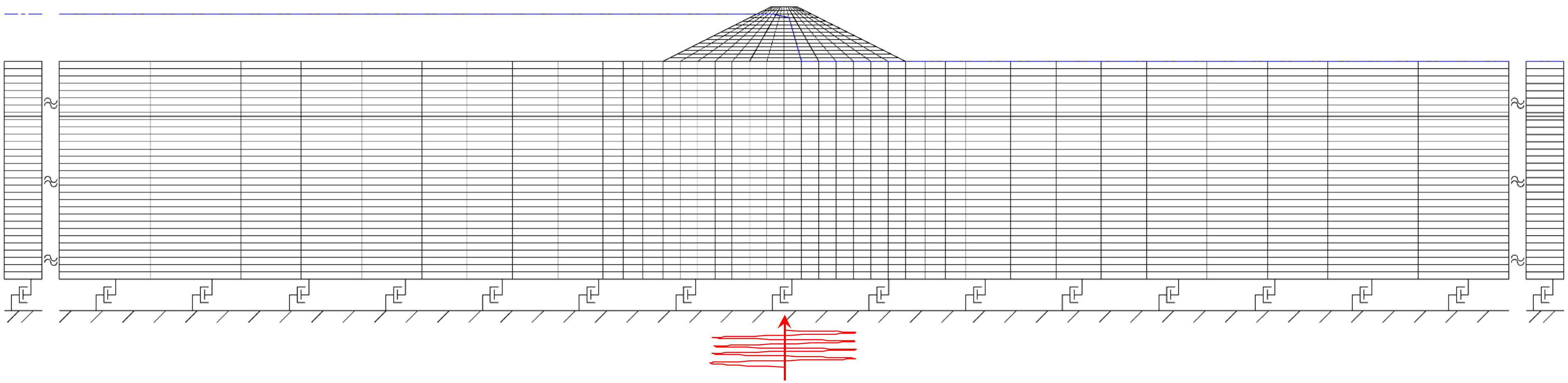
Searching for the slip circle providing the maximum displacement



Duttine et. al. (2015): Evaluation of seismic dam displacement by Newmark method taking into account soil strength reduction due to undrained cyclic loading, JGS Special Issue on earth dam seismic stability, 2015.03, pp.8-11, (in Japanese)

Tatsuoka et al. (2014). Evaluation of seismic slip displacement of slope by Newmark method taking into account soil strength reduction due to undrained cyclic loading and strain-softening, *Proc. Special JGS Symp. Overcoming the Great East Japan Earthquake*, pp.394-403, (in Japanese)

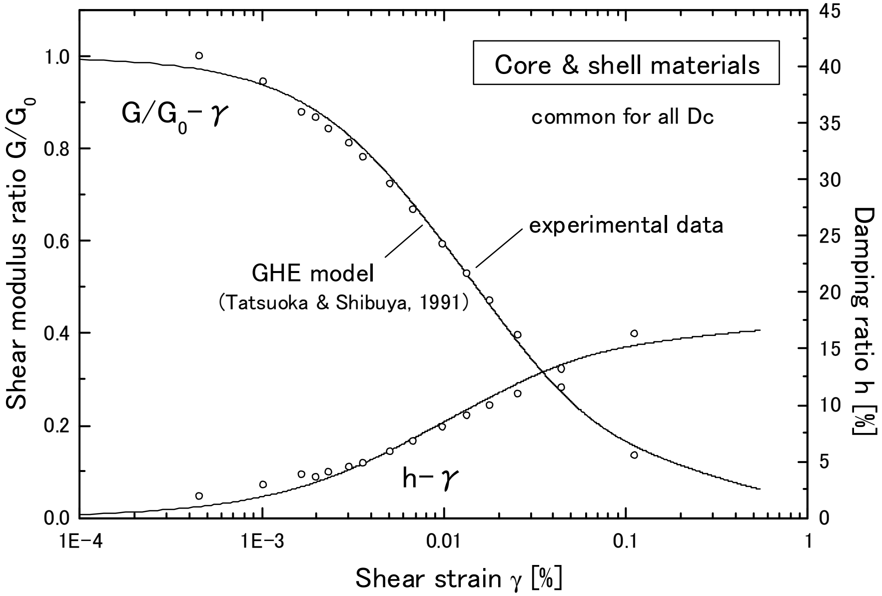
① Dynamic response analysis



⇨ No need for complicated constitutive model & analysis (effects of pore water pressure buildup will be taken into account later in modified Newmark)

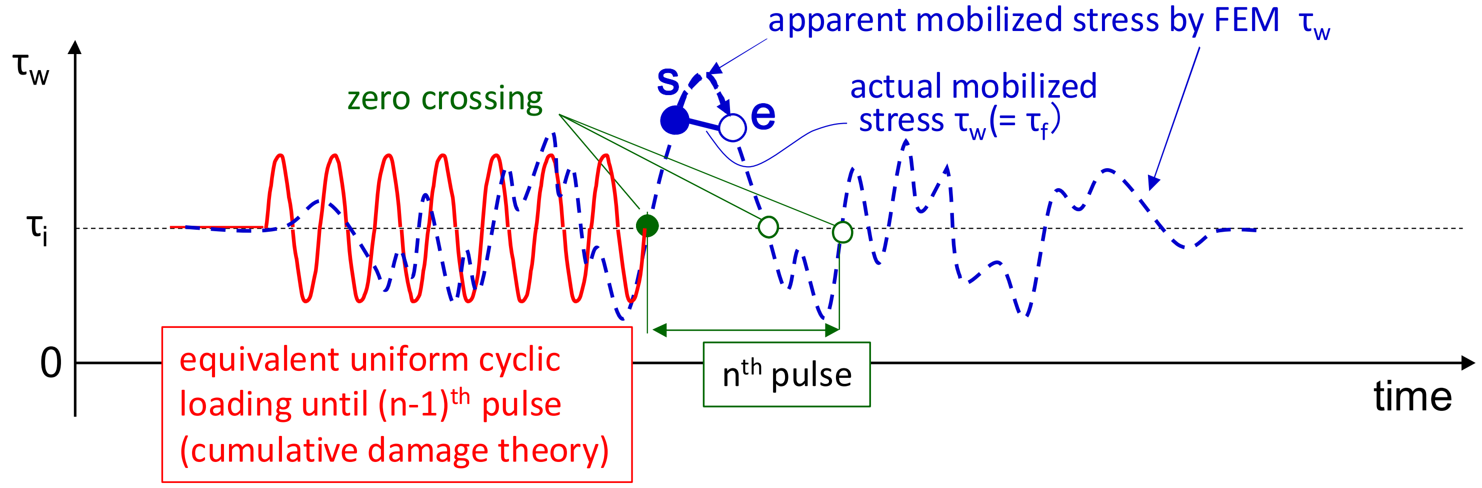
⇨ Hyperbolic model（Hardin-Drnevich, Generalized Hyperbolic Equation GHE model – Tatsuoka et al., 1991)

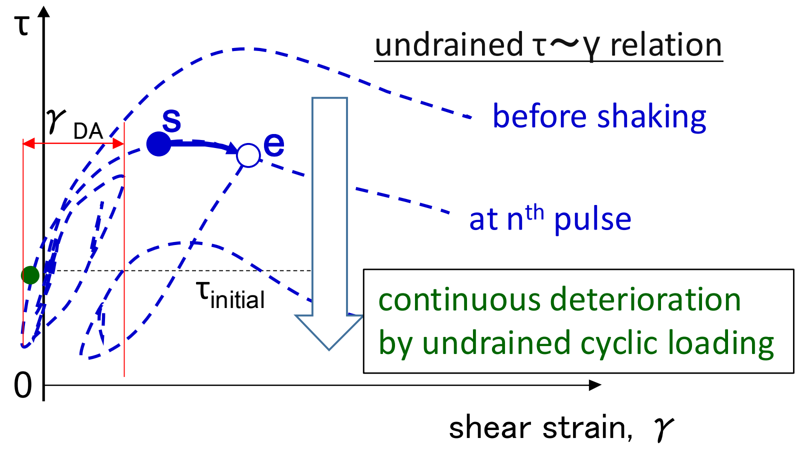
⇨ Simplified analysis: Linear equivalent

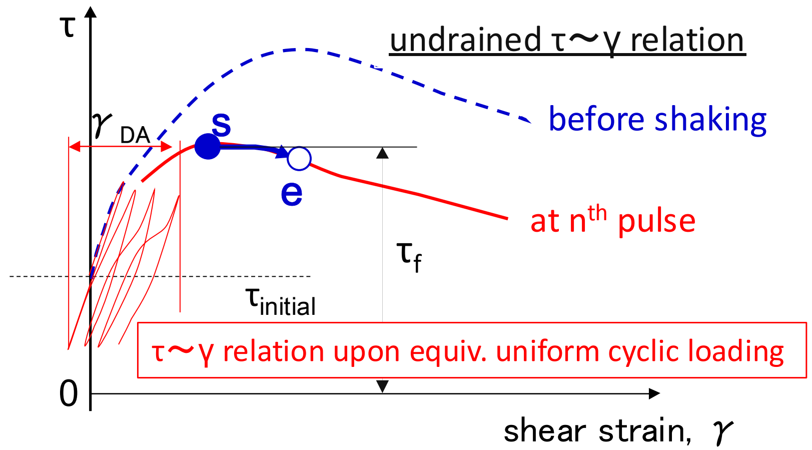


Tatsuoka,F. and Shibuya,S. (1991), "Deformation characteristics of soils and rocks from field and laboratory tests", Keynote Lecture for Session No.1, *Proc. of the 9th Asian Regional Conf. on SMFE,* Bangkok, Vol.II, pp.101-170.

⇨ In the analysis further, it will be assumed that yielding or slip occurs when apparent mobilized stresses by linear equiv. response analysis exceeds the deteriorating soil shear strength (computed based on cumulative damage)

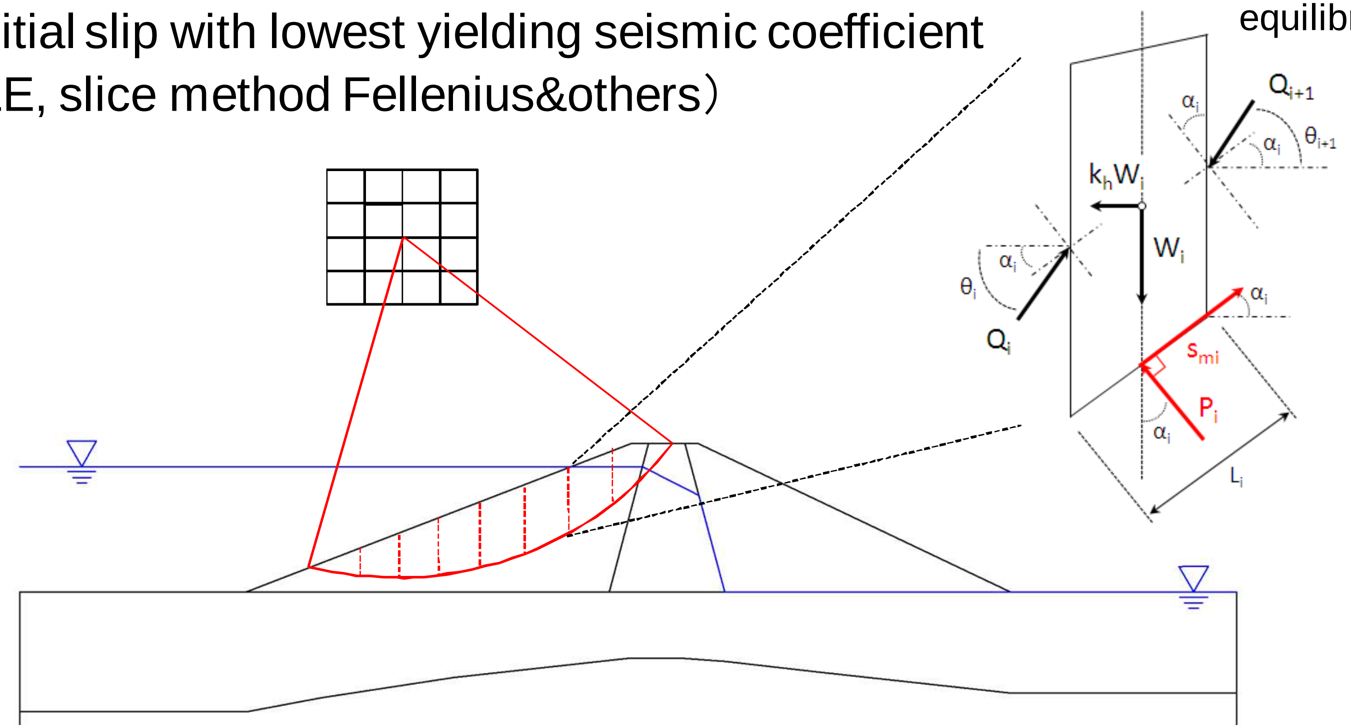






② Initial stability analysis (Limit Equilibrium: LE)

⇨ Initial slip with lowest yielding seismic coefficient
（LE, slice method Fellenius&others）



⇨ s_{mi} : undrained initial shear strength

$$s_{mi} = \frac{[P_i]_0' \tan\phi_u + c_u \cdot L_i}{F_s} \Leftrightarrow \tau_i = \frac{\sigma_0' \tan\phi_u + c_u}{F_s}$$

F_s : safety factor

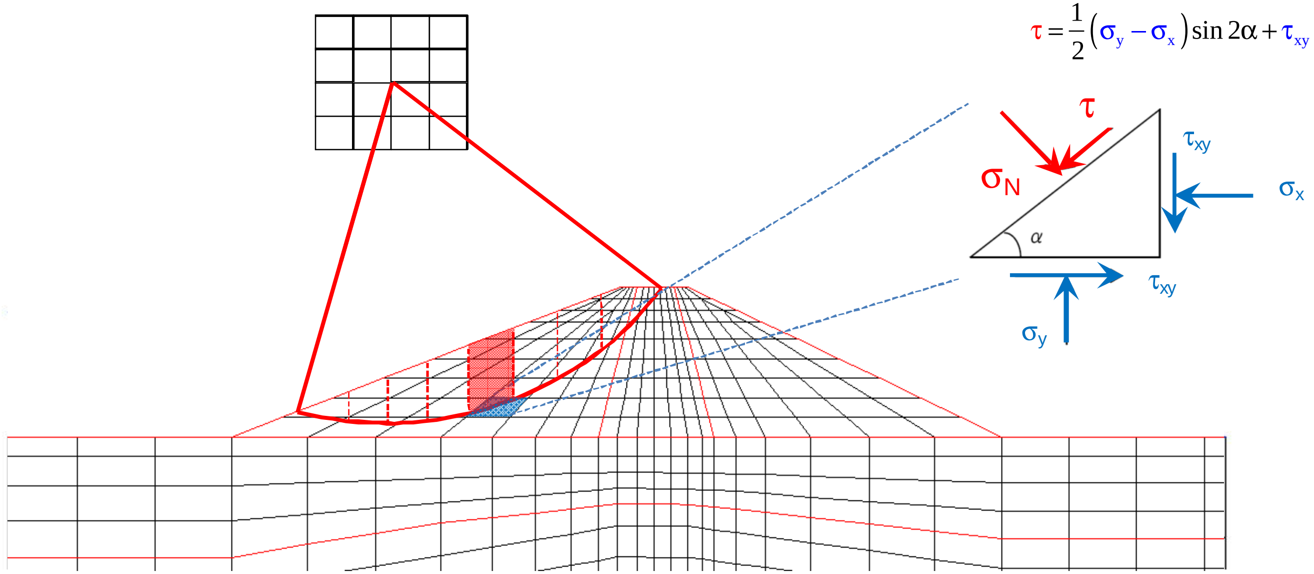
⇨ σ_0' : initial effective normal stress
c_u, ϕ_u : apparent undrained cohesion, friction angle (total stress),
that are progressively degraded by undrained cyclic loading (CL)

③ Random cyclic loading used in cumulative damage

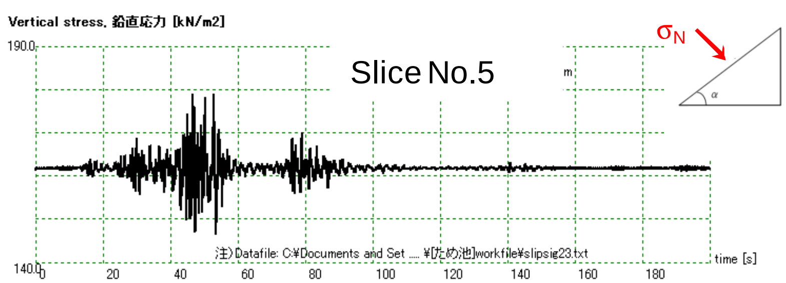
⇨ Simply obtained for each slice by projecting the stresses of nearest element along the slice base plane

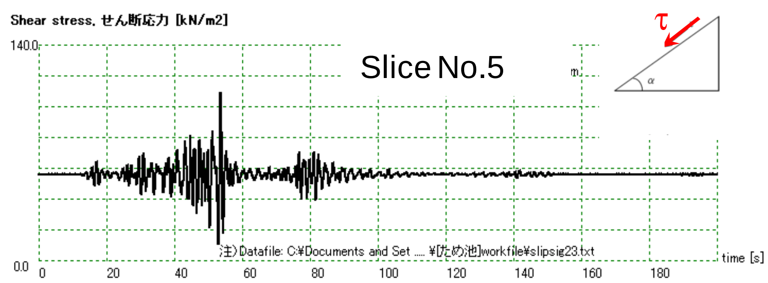
$$\sigma_N = \frac{1}{2}(\sigma_x + \sigma_y) + \frac{1}{2}(\sigma_y - \sigma_x)\cos 2\alpha - \tau_{xy} \sin 2\alpha$$

$$\tau = \frac{1}{2}(\sigma_y - \sigma_x)\sin 2\alpha + \tau_{xy} \cos 2\alpha$$



⇨ Normal and shear stress time histories for each slice

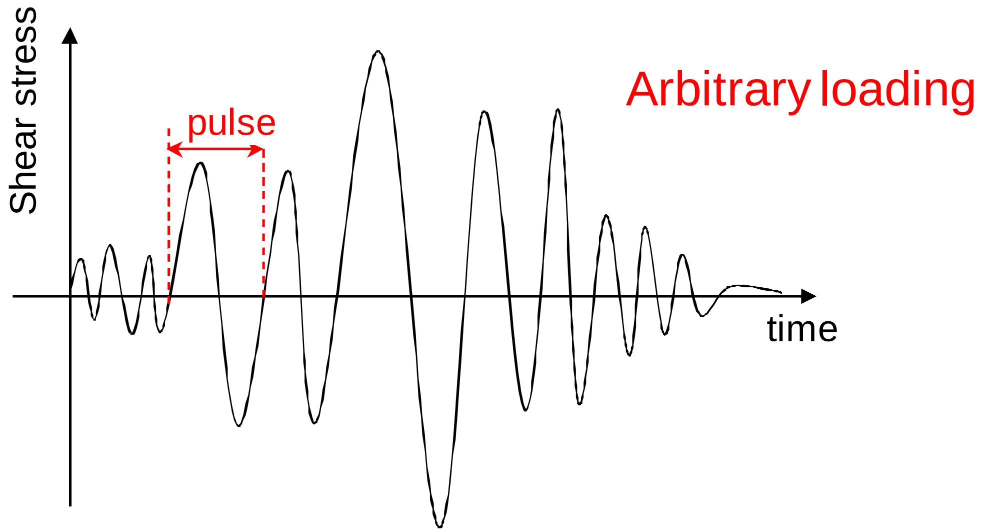


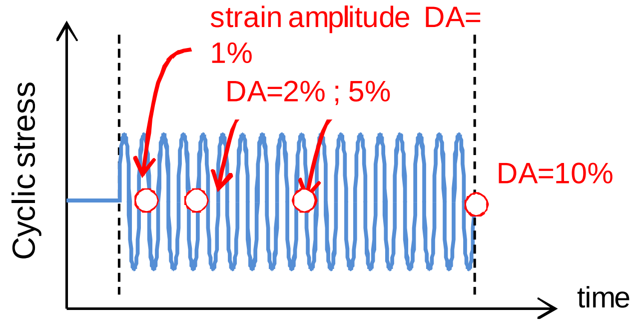


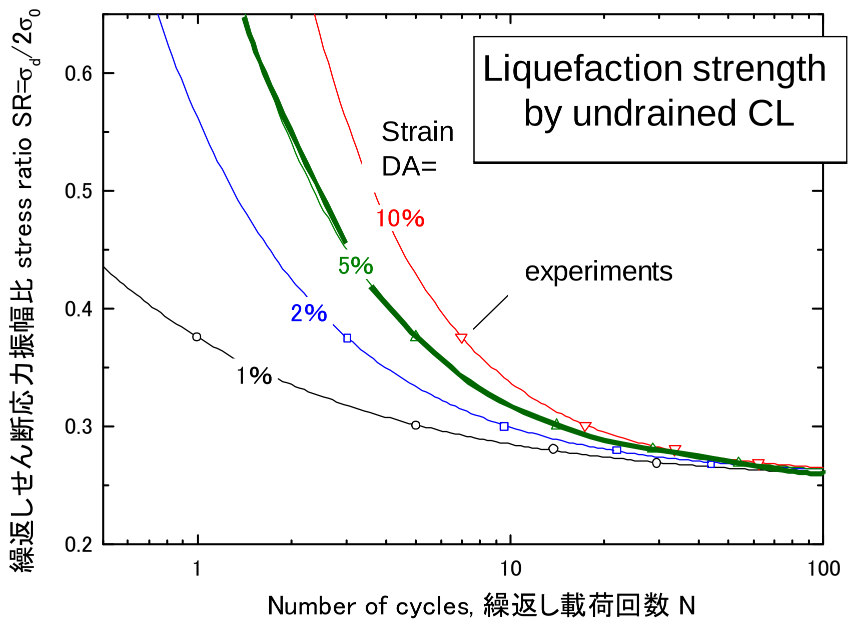
③ Cumulative damage concept

Donovan, N. C. (1971): "A stochastic approach to the seismic liquefaction problem," Proceedings of the 1st International Conference on Application of Statistics and Probability to Soil and Structural Engineering, Hong Kong, September.

⇨ Damage by an individual pulse of an arbitrary loading







Damage

$$D = \frac{1}{N_c}$$

N_c is the equivalent number of cycles of same amplitude as that of individual pulse and that will lead to a damage D=1

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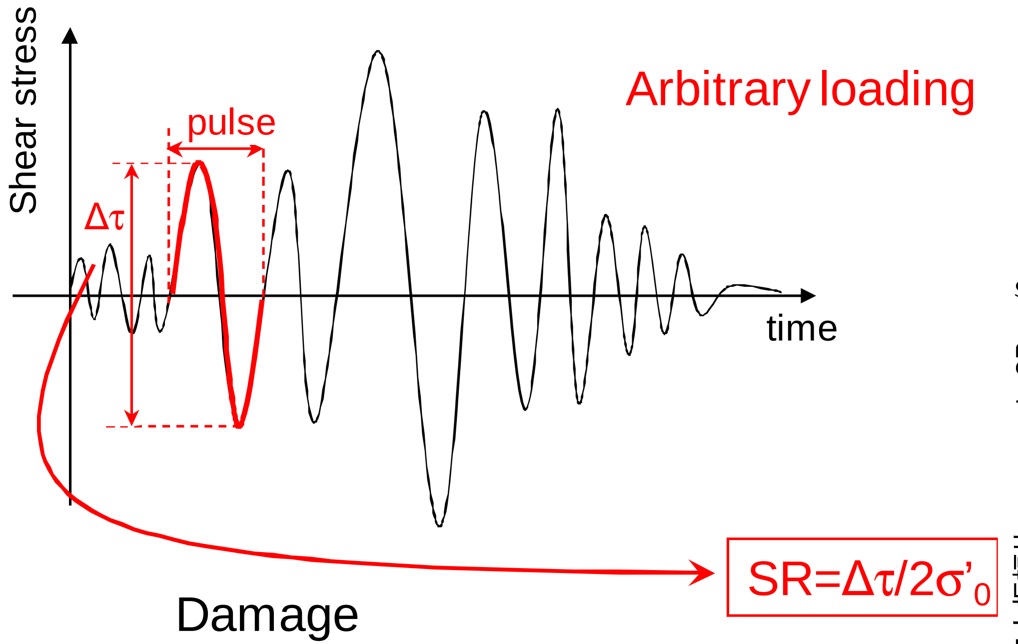
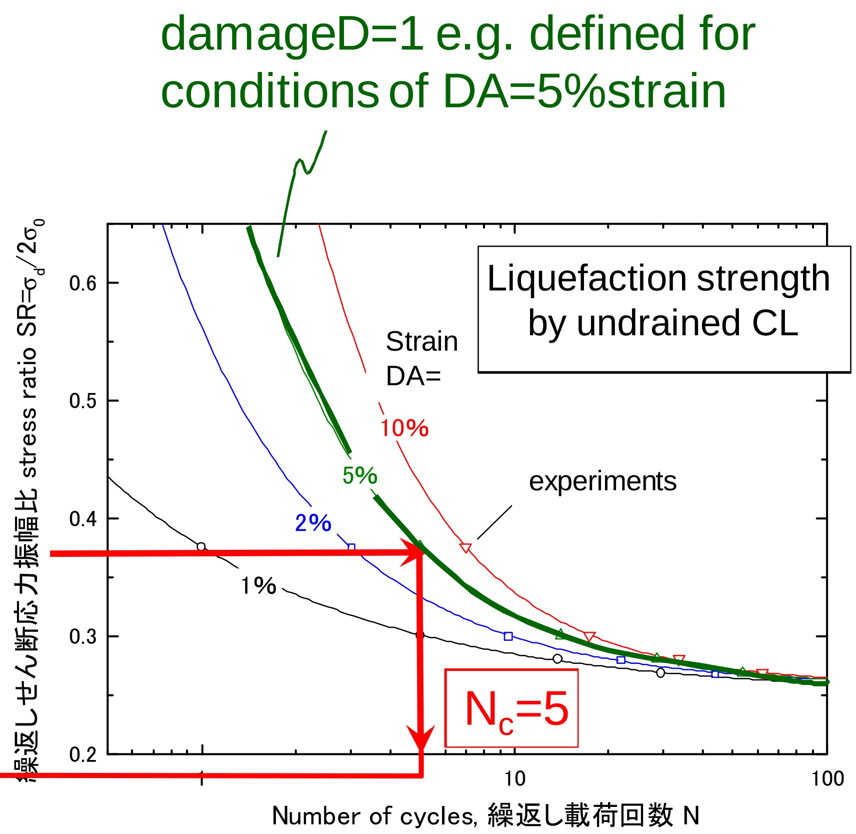
⇨ Damage by an individual pulse of an arbitrary loading



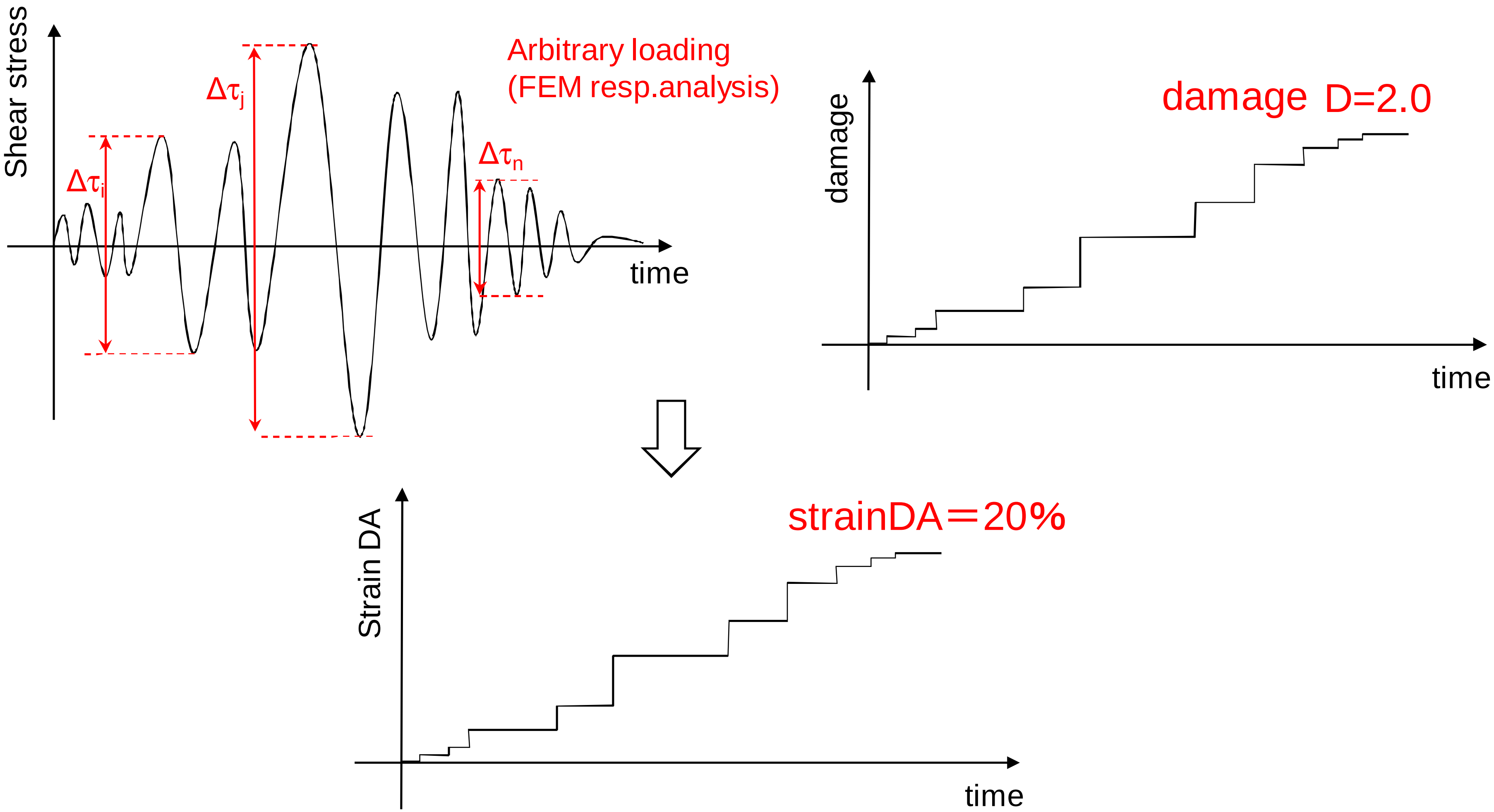


$$D = \frac{1}{N_c} = \frac{1}{5}$$

N_c is the equivalent number of cycles of same amplitude as that of individual pulse and that will lead to a damage D=1

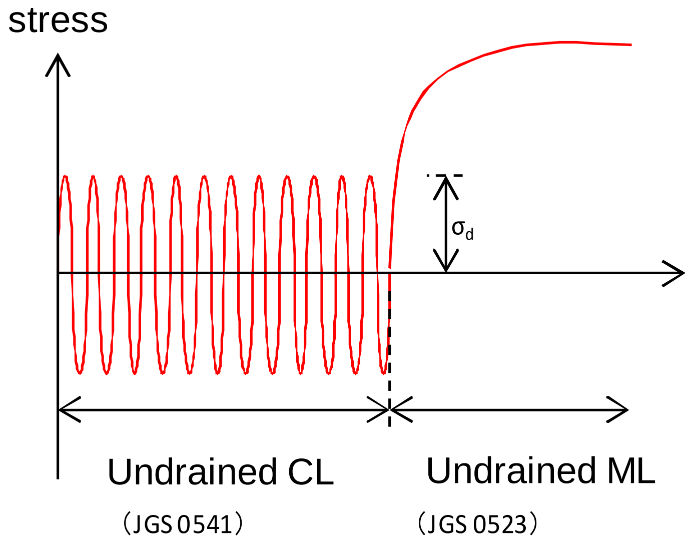
③ Cumulative damage concept

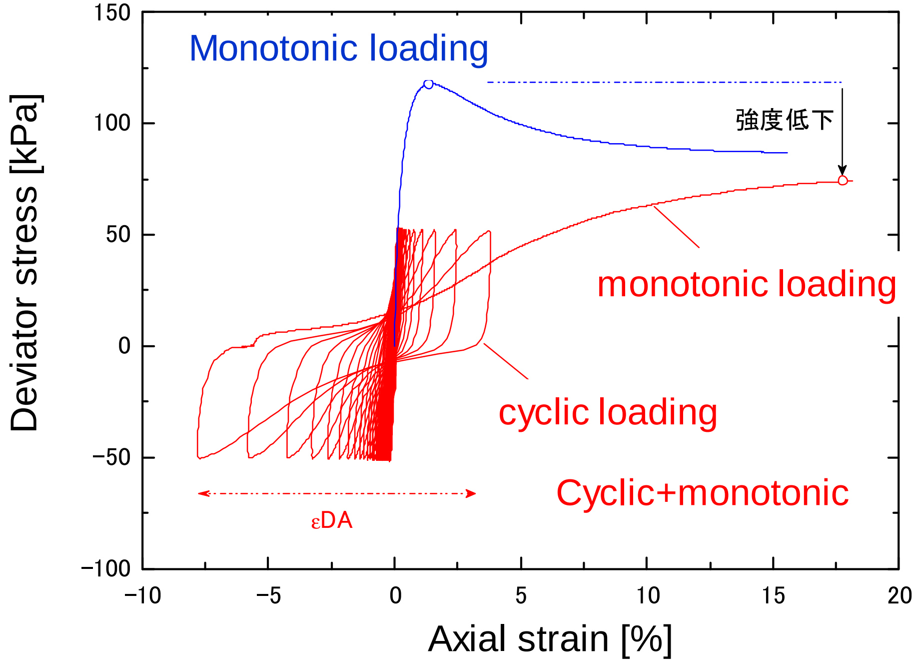
⇨ Time history of accumulated damge each slice, from which time history of equivalent strain amplitude is backcalculated by dichotomy



③ Degradation of shear strength

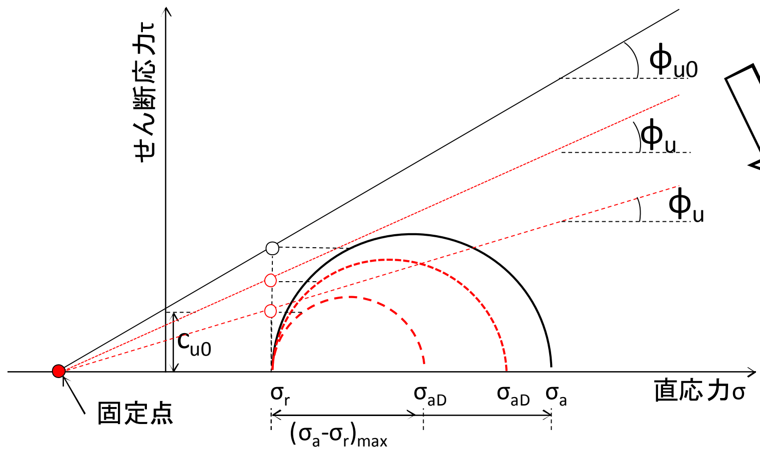
⇨ Obtained experimentally by undrained cyclic loading followed by monotonic loading tests





Strain amplitude
DA=1%,2%,5%,10%

Monotonic loading

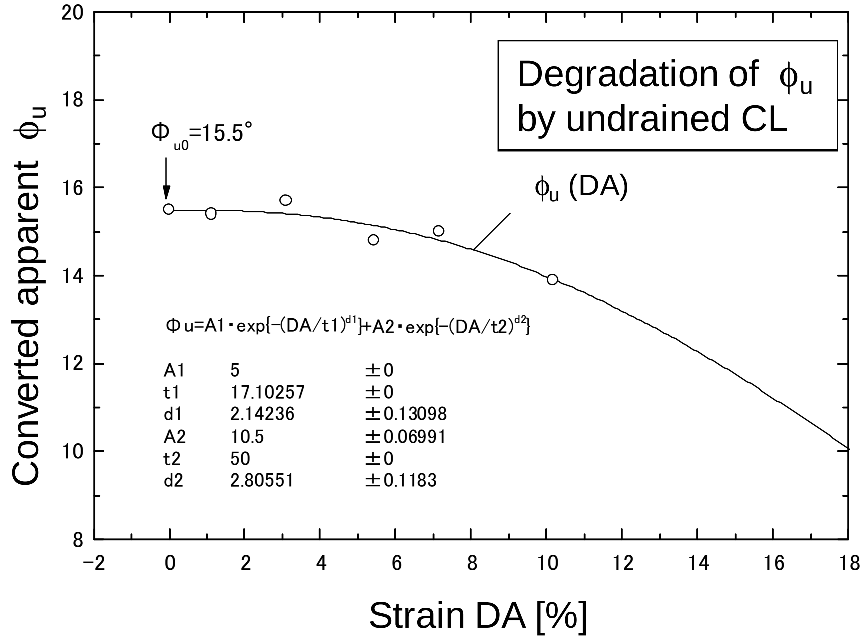


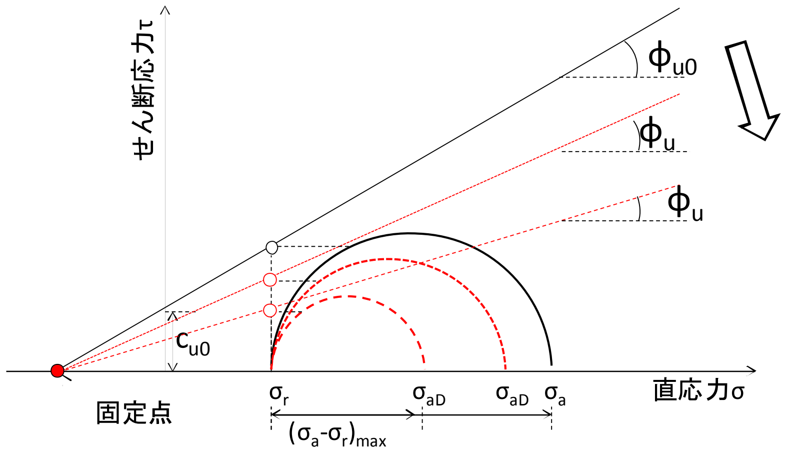
Degradation of apparent c_u,φ_u
(total stress)

③ Degradation of shear strength

⇨ Obtained experimentally by undrained cyclic loading followed by monotonic loading tests

C_{u0}, ϕ_{u0}: initial undegraded strength by undrained ML without CL (DA=0%)



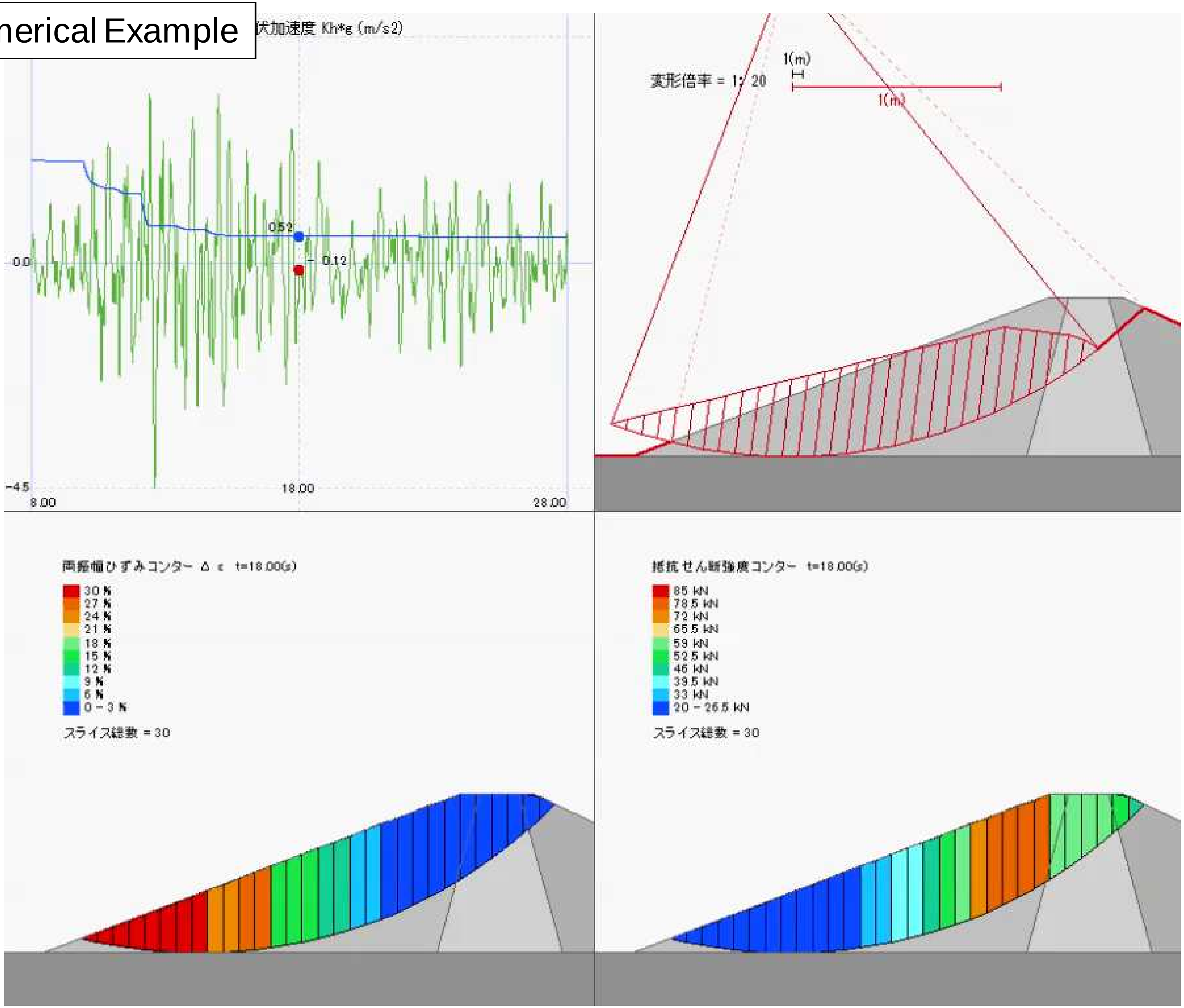


Degradation of apparent c_u, ϕ_u (total stress method)

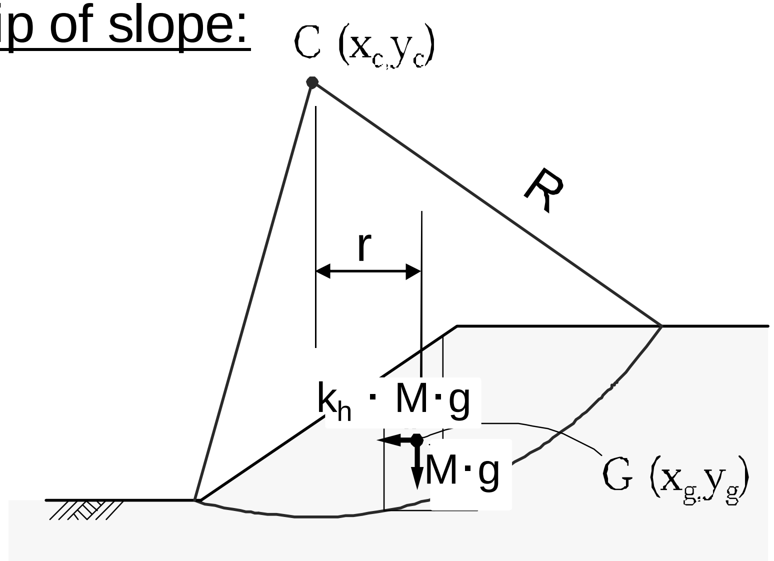
Degradation of tan ϕ_u & c_u proportional

$$\frac{c_u}{c_{u0}} = \frac{\tan\phi_u}{\tan\phi_{u0}}$$

Numerical Example



Newmark: Force equilibrium in circular slip of slope:



Resisting moment

$$M_r = \sum \{R \cdot (\tau_{fi} \cdot l_i)\}$$

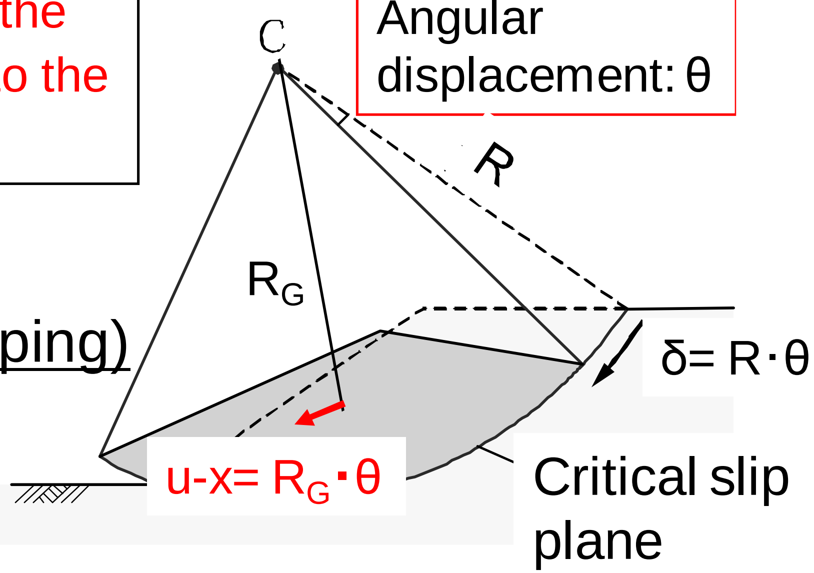
$$\tau_{fi} = c_i + \sigma_{n.i} \cdot \tan \phi_i$$

Disturbing moment

$$M \cdot g \cdot r + M \cdot R_G \cdot \frac{\partial^2 u}{\partial t^2}$$

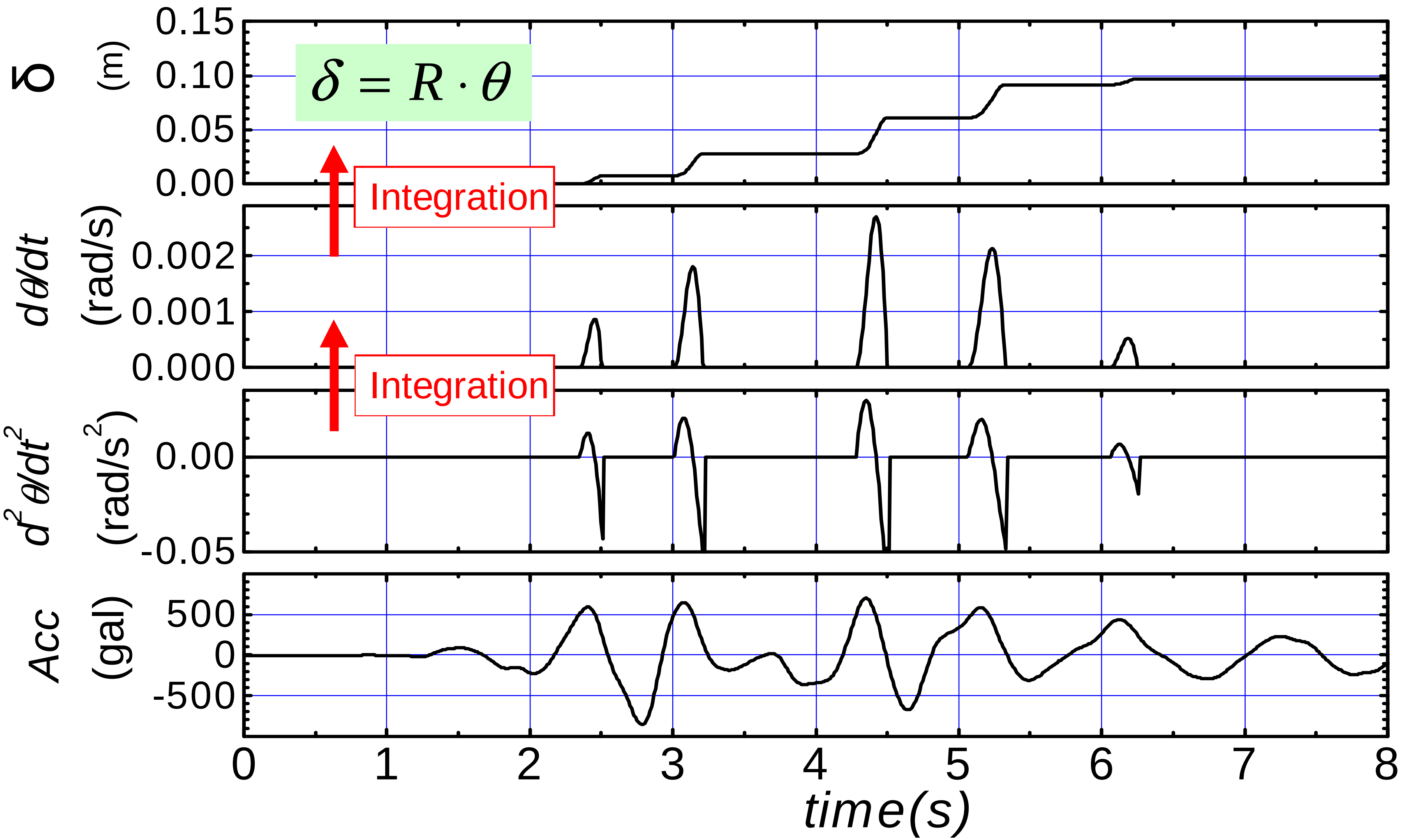
Slice method

u-x= R_G･θ: displacement in the slip direction at the gravity center of the sliding mass relative to the supporting ground



Force equilibrium when $F_s > 1.0$ (not slipping)

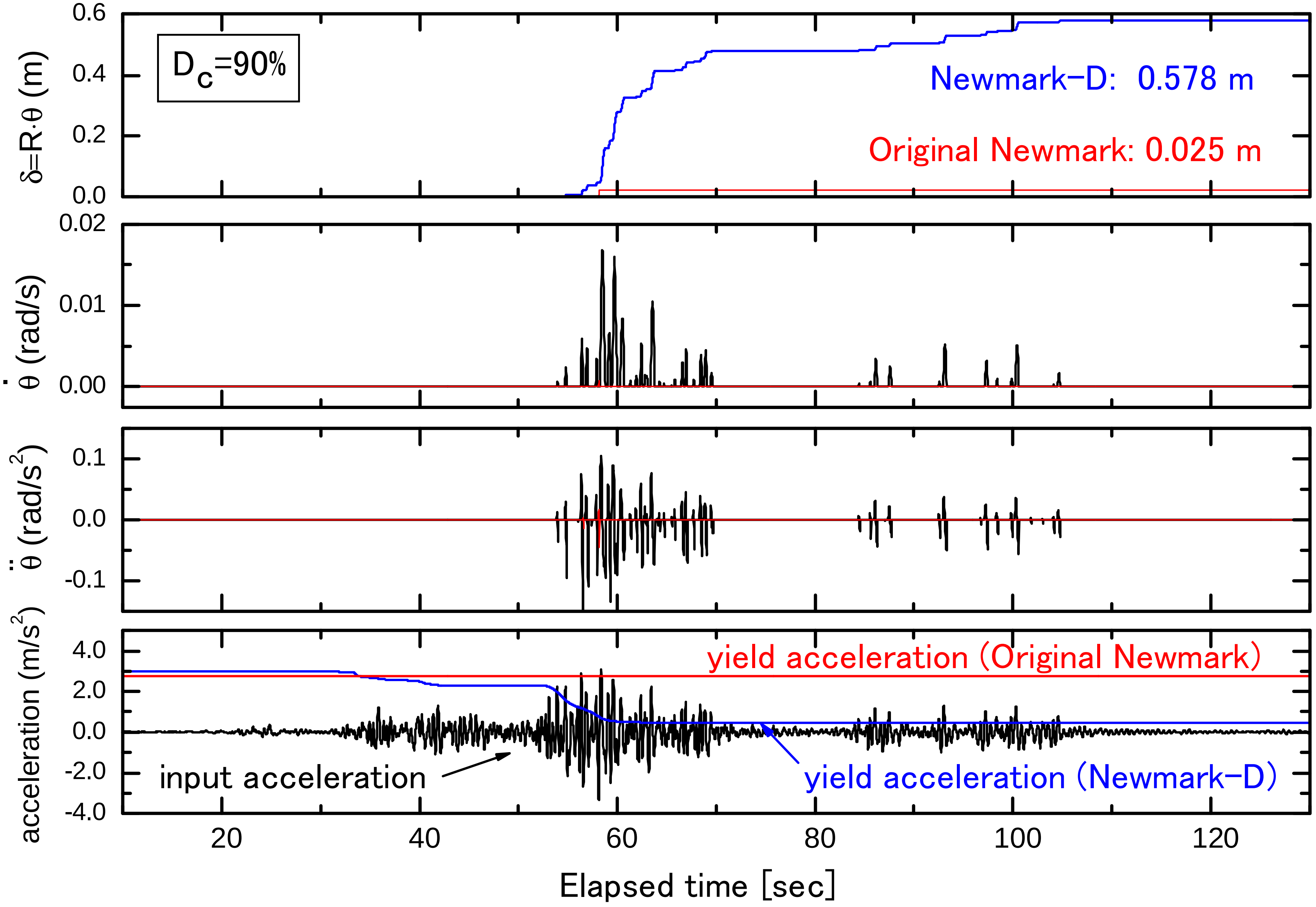
$$M_r > M \cdot g \cdot r + M \cdot R_G \cdot \frac{\partial^2 u}{\partial t^2}$$



$$M \cdot (R_G)^2 \cdot \frac{\partial^2 \theta}{\partial t^2} = M_d - M_r$$

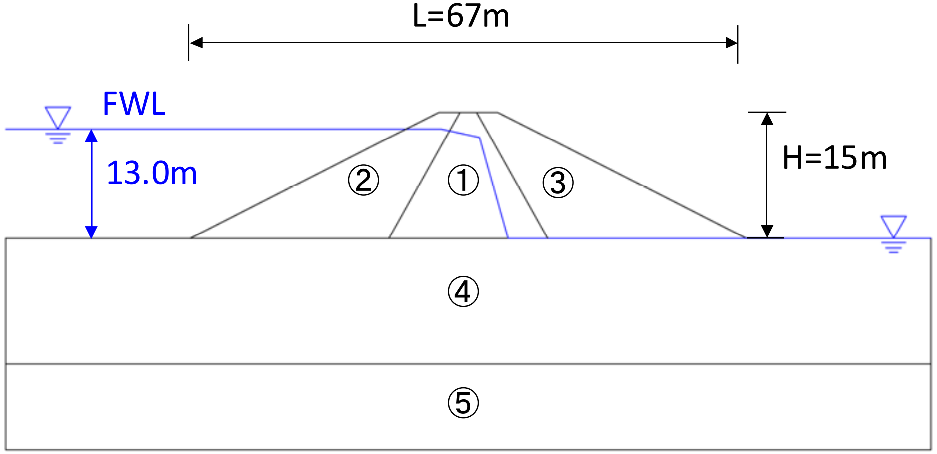
⇒Obtain slip displacement
x-u=R･θ from:

$$\ddot{\theta} = \frac{M_d - M_r}{M \cdot (R_G)^2}$$



D_c=90%
Newmark−D: 0.578 m
Original Newmark: 0.025 m
δ=R·θ (m)
θ̇ (rad/s)
θ̈ (rad/s²)
acceleration (m/s²)
yield acceleration (Original Newmark)
input acceleration
yield acceleration (Newmark−D)
0.6
0.4
0.2
0.0
0.02
0.01
0.00
0.1
0.0
-0.1
4.0
2.0
0.0
-2.0
-4.0
20
40
60
80
100
120
Elapsed time [sec]

Analysis examples: Newmark-D



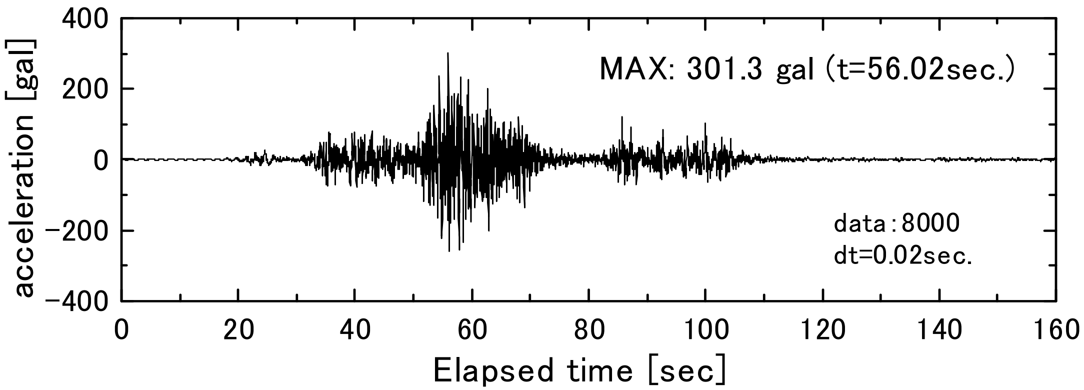
⇨ Compacted to $(D_c)_{1Ec}$=85% ; 90% ; and 95%

	Dc [%]	γ_t [kN/m^3]	γ_{sat} [kN/m^3]	c' [kPa]	ϕ' [deg]	c_u [kPa]	ϕ_u [deg]
①②③ core & shell	95	18.2	19.8	1 (0*)	50(35*)	45	20
	90	17.2	19.2	7 (0*)	40(35*)	15	25
	85	16.3	18.7	5 (0*)	35(35*)	4	32
④⑤ subgrade	--	21.0	21.0	37	31.5	37	31.5

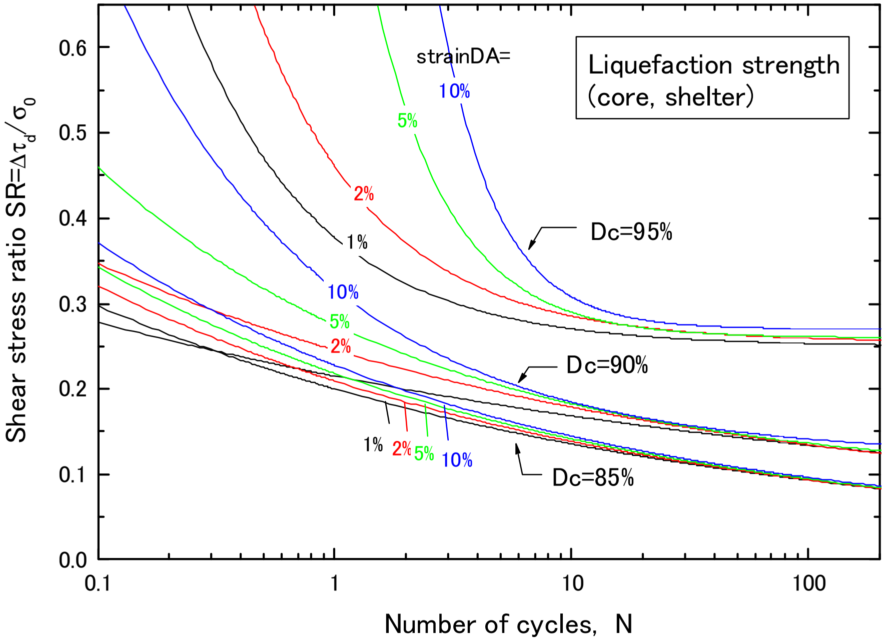
* residual strength values

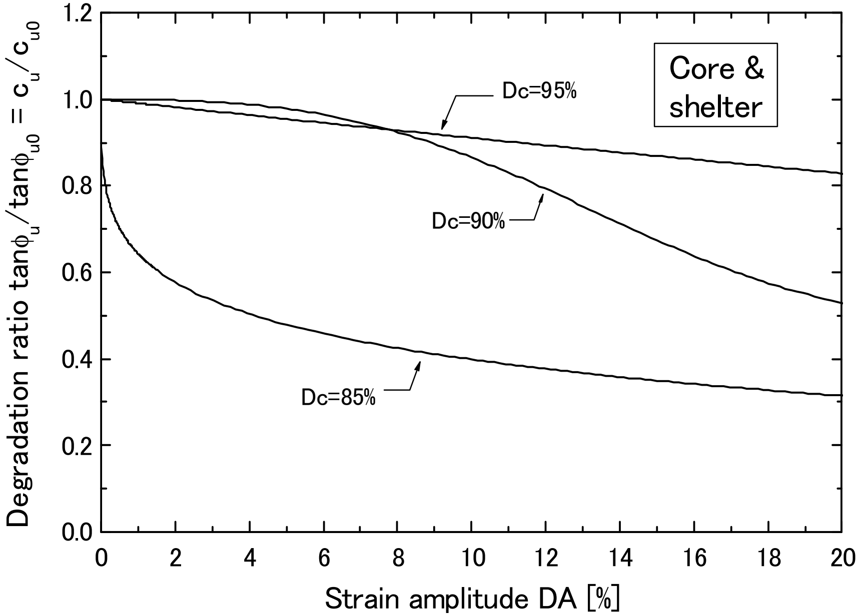
Analysis examples: Newmark-D

Input motion (Nankai trough)



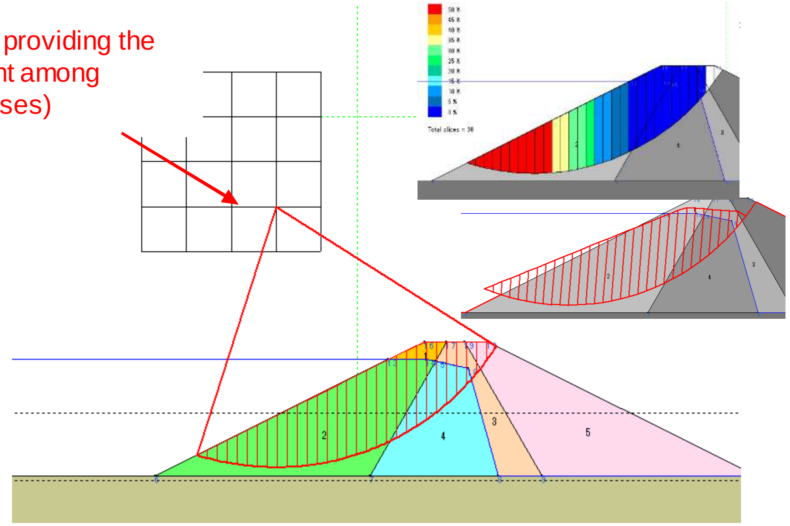
⇨ Results of undrained cyclic & monotonic loading tests





Results of analysis

Critical failure plane providing the maximum δ (different among different analysis cases)

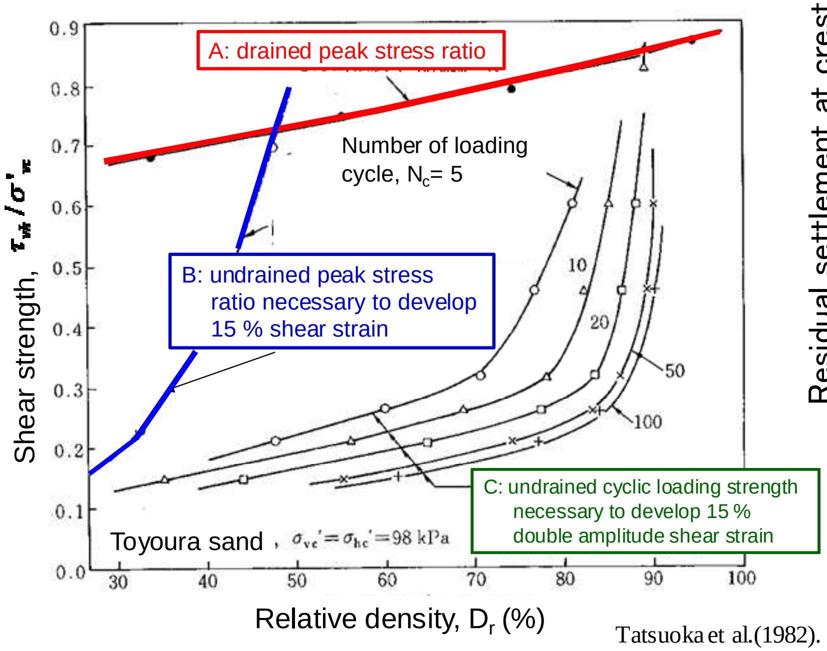


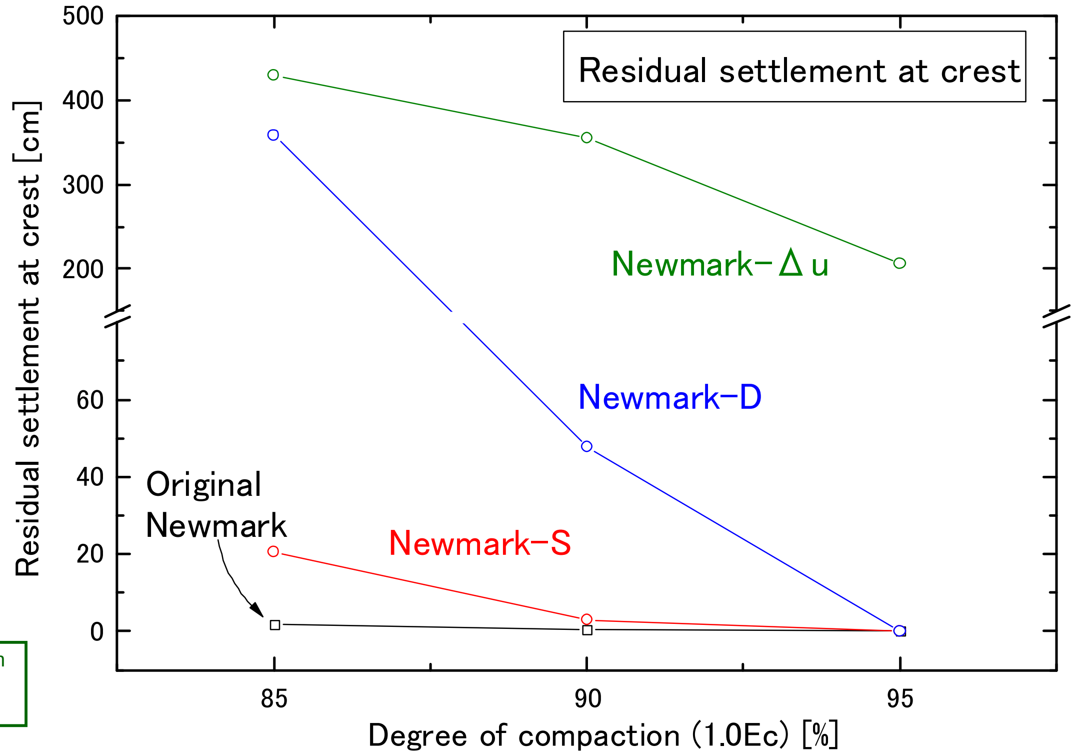
<u>Newmark-D:</u>

- Due to the use of degrading undrained strength, effects of $(D_c)_{1Ec}$ on the slip displacement are significant.
- Realistic for the submerged upper-reach slope.

<u>Existing Newmark approaches (O,S,Δu):</u>

- Due to the use of drained strength, effects of Dc are small (Original, S)
- Due to difficult estimation of Δu at failure (cyclic mobility..), settlement for Dc=95% overestimated (Δu)





Tatsuoka et al.(1982). Cyclic undrained stress-strain behavior of dense sands TSS tests, *S&F* Vol22(2):55-70.

SUMMARY

1. OUTLINE AND BACKGROUND

2. MODIFIED NEWMARK SLIDING BLOCK ANALYSIS

Procedure

Analysis example

3. PSEUDO-STATIC FEM ANALYSIS

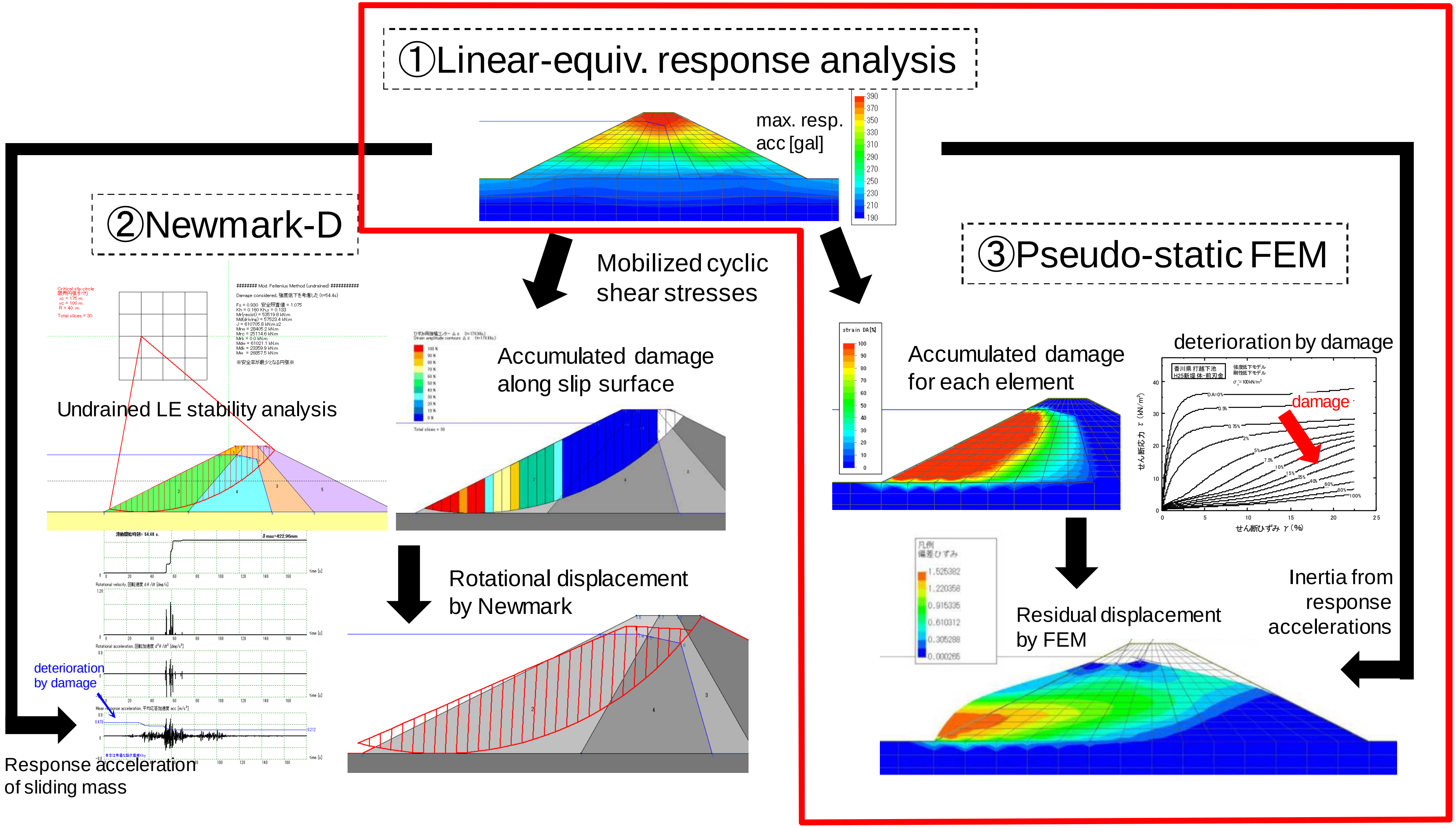
Procedure

Analysis example

4. COMBINATION OF NEWMARK-D AND PSEUDO-STATIC FEM ANALYSES

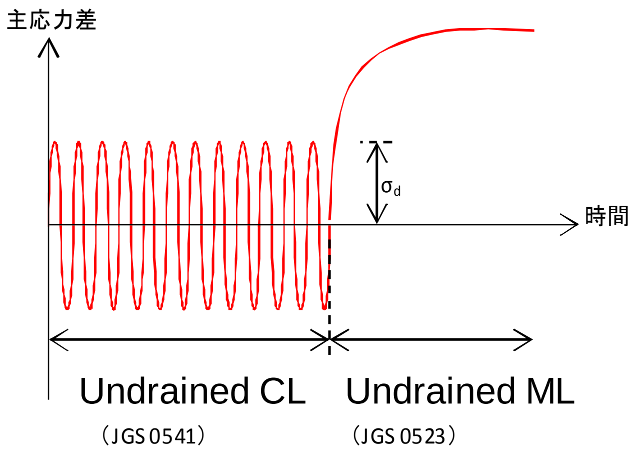
5. CONCLUSION

⇨ Development of modified Newmark method and pseudo-static FEM analyses in a united framework (cumulative damage and total stress concepts) along with relevant undrained cyclic+monotonic loading tests



Degradation of stress strain properties by undrained CL

・obtained from same CL+ML test results as for Newmark (no additional experiments)



$$y = f_0(x)\cdot x^{m_1+(m_2-m_1)\cdot x} + a\left[e^{-b\cdot x^c}\cdot\frac{x}{1+x} - \frac{x}{2e^b}\right]$$

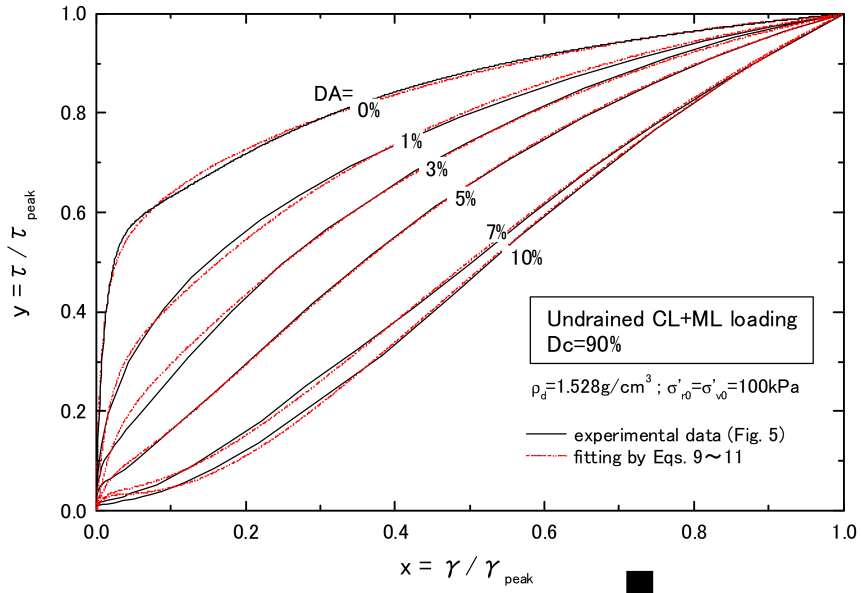
・$y = \tau/\tau_{peak}$、$x = \gamma/\gamma_{peak}$: normalized peak stress strain

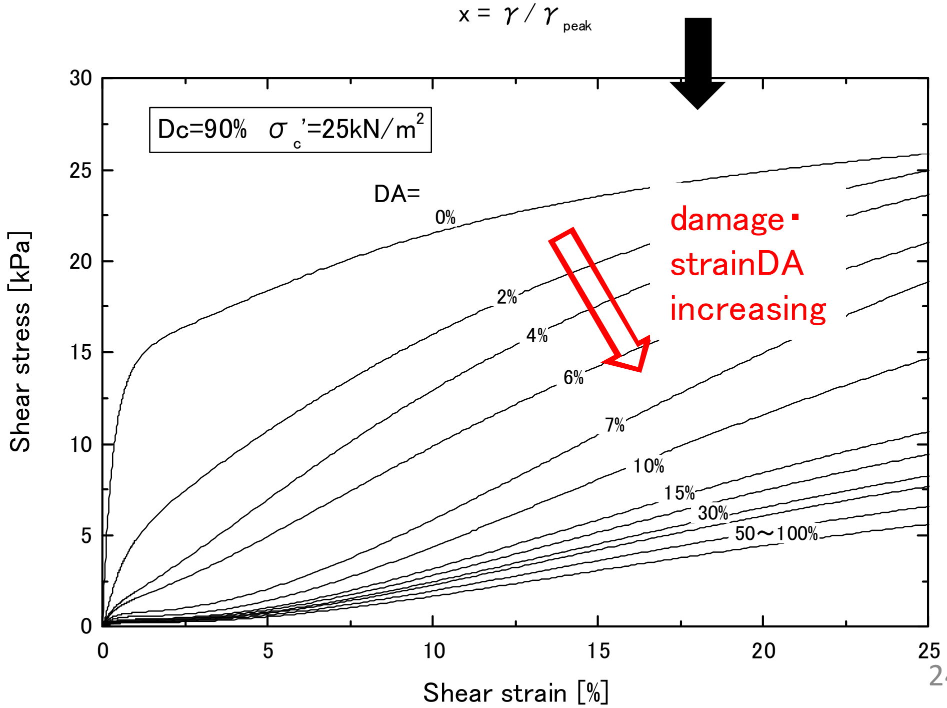
・$f_0(x)$: GHEmodel (backbone curve DA=0%: 5 parameters)

・m1,m2,a,b,c : 5 parameters that may depend on DA

・τ_{peak}-DA : degradation of peak strength used in NewmarkD

Undrained CL followed by ML
Normalized relations



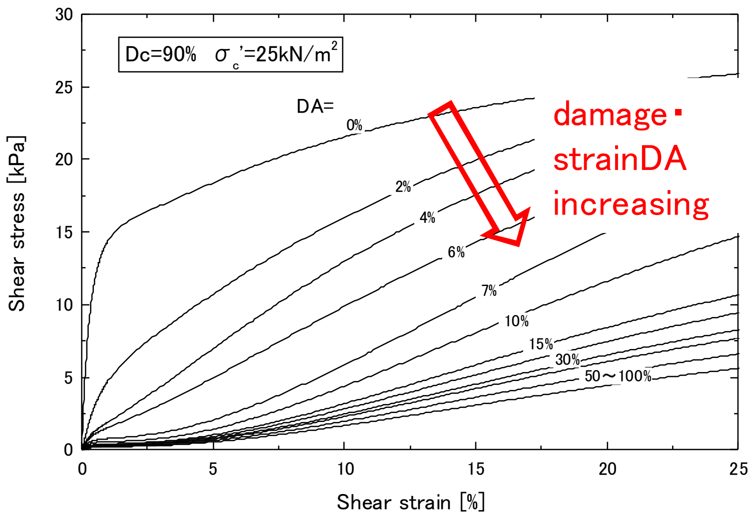


pseudo-static FEM analysis

※ constitutive relation (nonlinear elas.)

$$\boldsymbol{\sigma} = -K \cdot \varepsilon_v \cdot \mathbf{1} + 2\frac{\tau(e)}{e}\mathbf{e}$$

volumetric   deviatoric



$$K = K_i + K_w / n$$ total bulk modulus

$$K_i = \frac{2(1+\nu_0)}{3(1-2\nu_0)} G_{50}$$: bulk modulus of granular skeleton (constant)

K_w: water bulk modulus（=2.15GPa） n: porosity

※ Taking into account inertia derived from nodes response accelerations

constitutive relation

内力 $\mathbf{F}^{int}(\mathbf{d}) = \int_\Omega \mathbf{B}^T \boldsymbol{\sigma}(\mathbf{d}) d\Omega$

外力 $\mathbf{F}^{ext} = -\int_\Omega \rho \mathbf{N}^T \ddot{\mathbf{u}}_t d\Omega - \int_\Omega \rho \mathbf{N}^T \mathbf{g} d\Omega$

Inertia by resp.acc   gravity

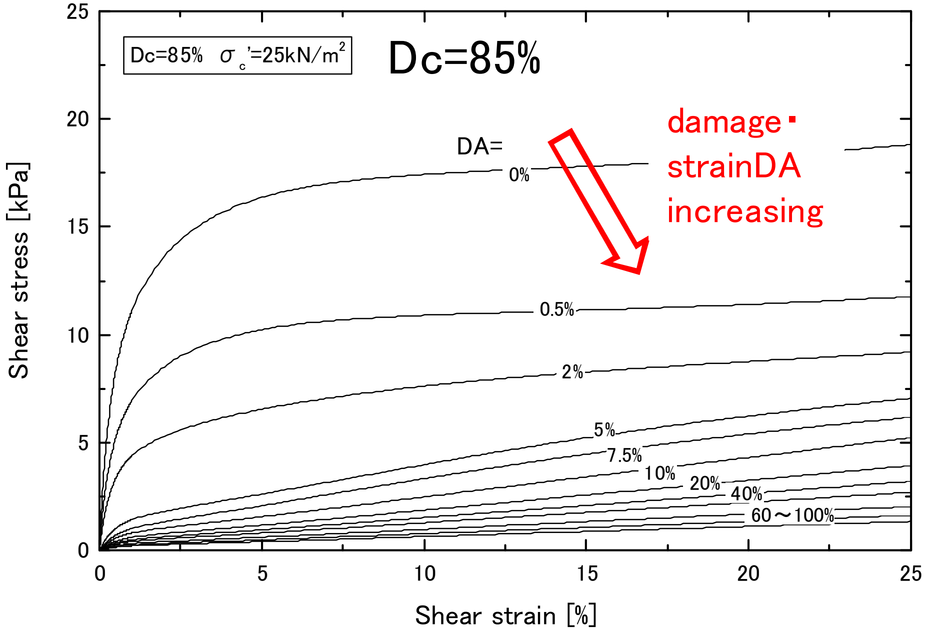
$\mathbf{d}$: node displacement (unknown)
$\mathbf{N}, \mathbf{B}$: shape function and its spatial differentiation

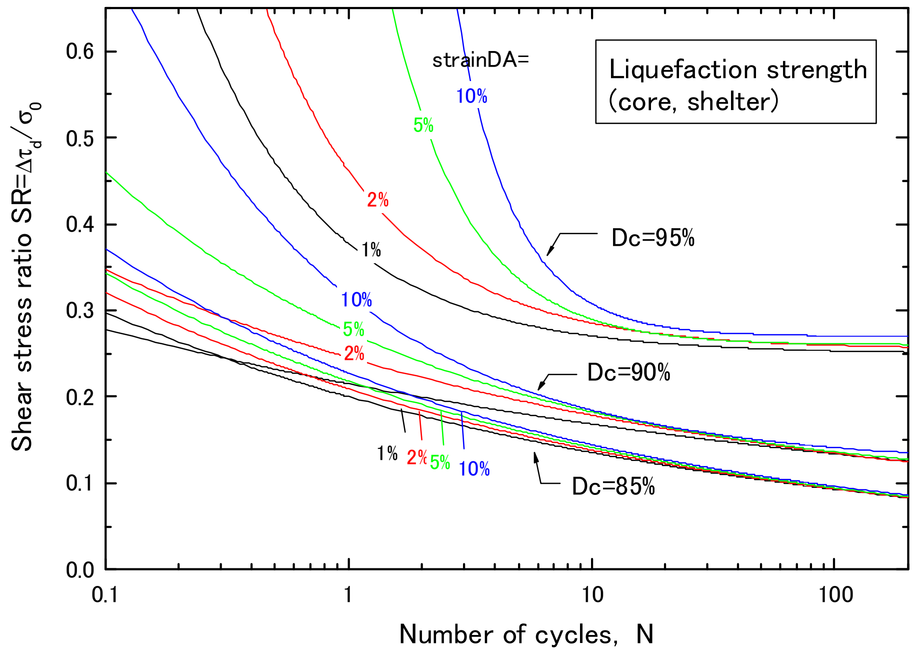
$\mathbf{g}$: gravity acceleration

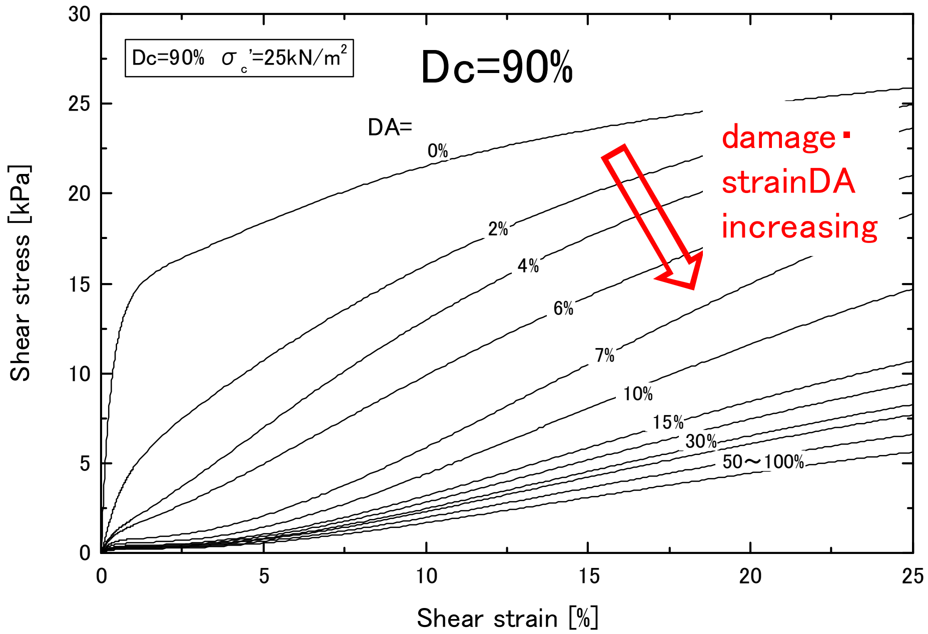
$\ddot{\mathbf{u}}_t = \mathbf{N}\ddot{\mathbf{d}}_t$ node response acceleration obtained from response analysis.

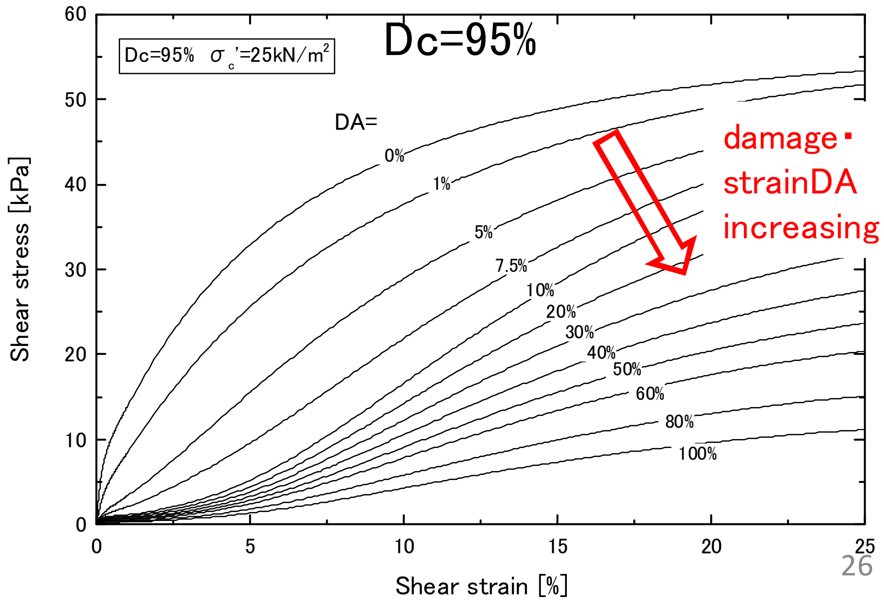
※ Volumetric locking countermeasure: Selective Reduced Integration
or 2nd order element（serendipity elem.）

Analysis examples : effects of Dc

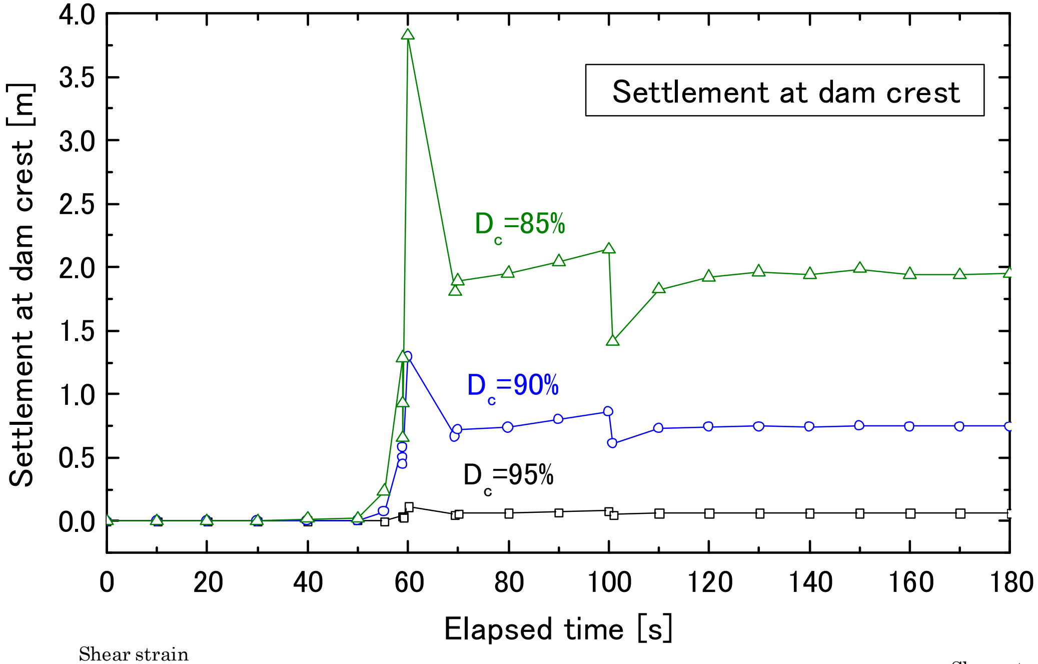


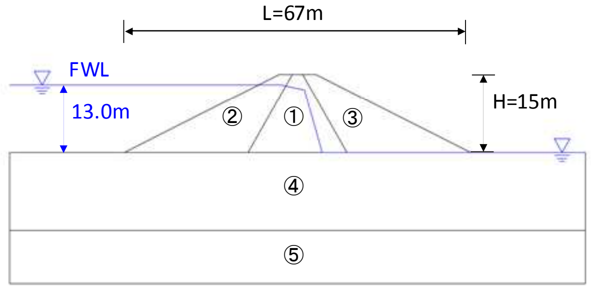


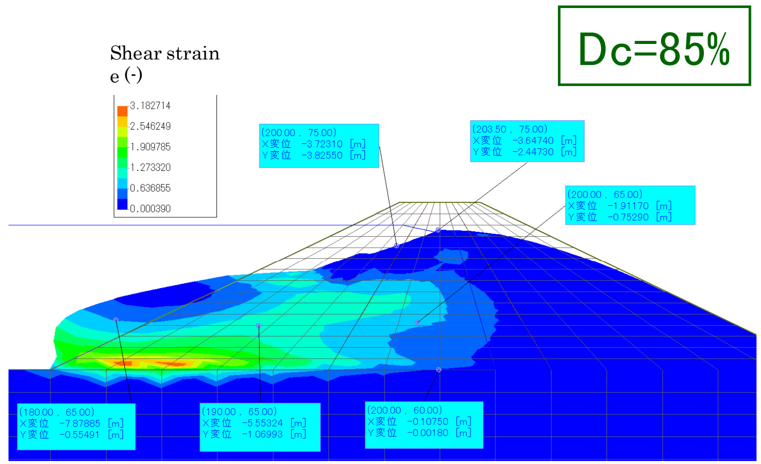


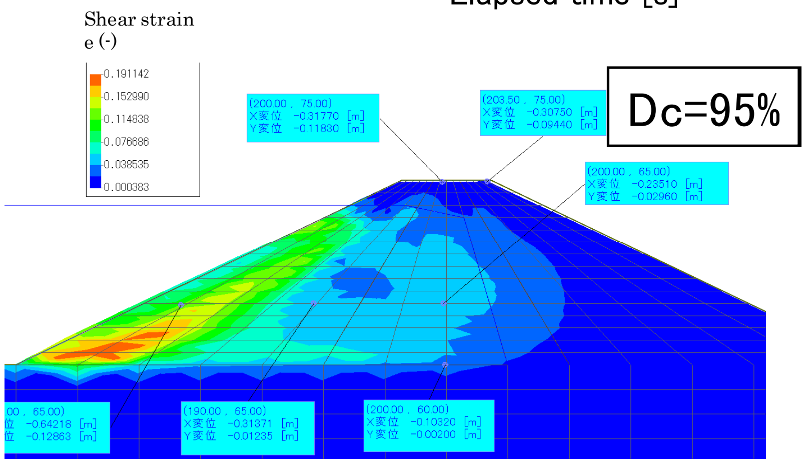


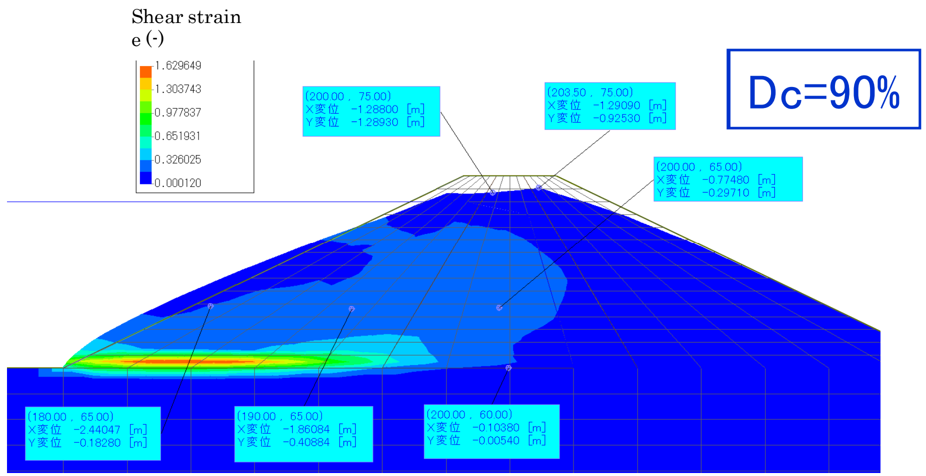
Analysis examples : effects of Dc





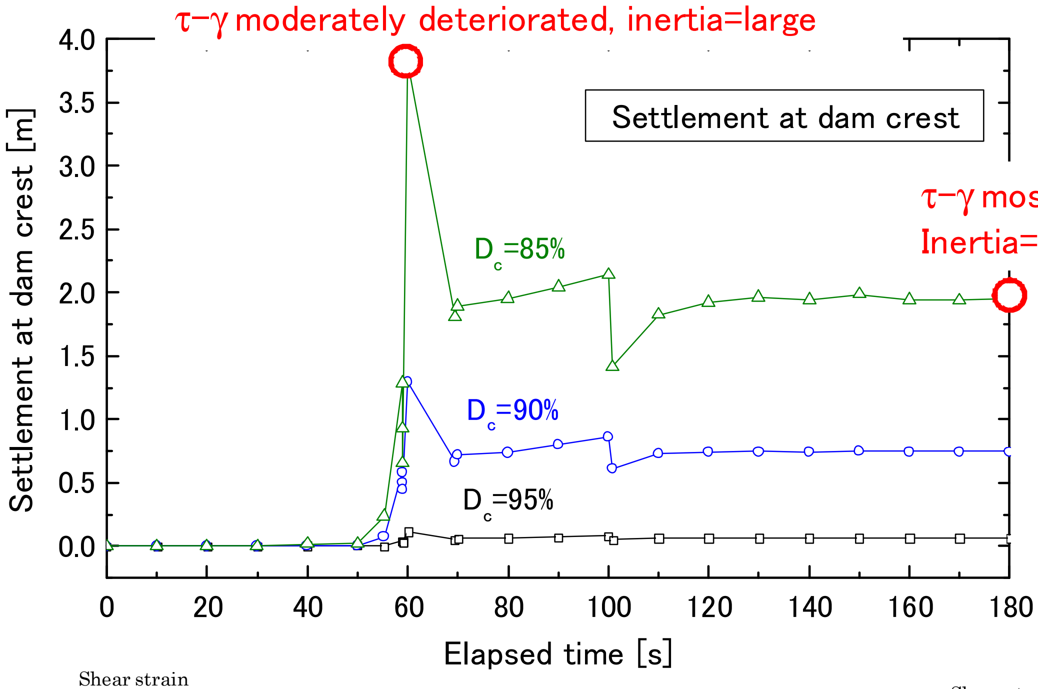


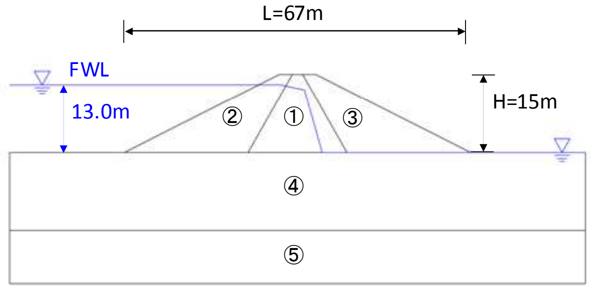


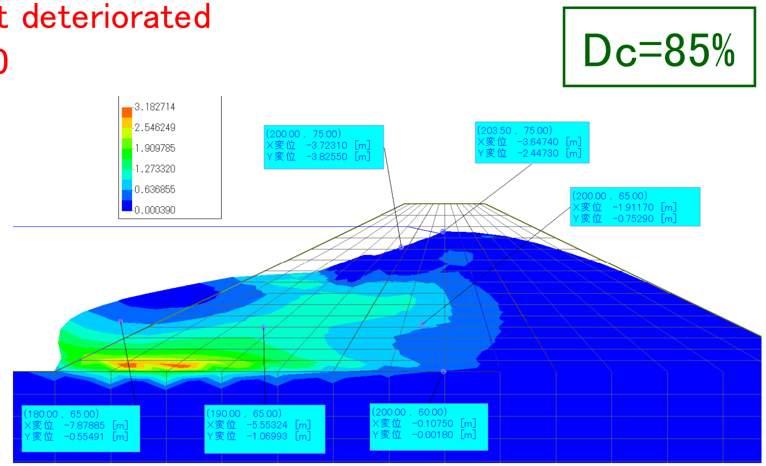


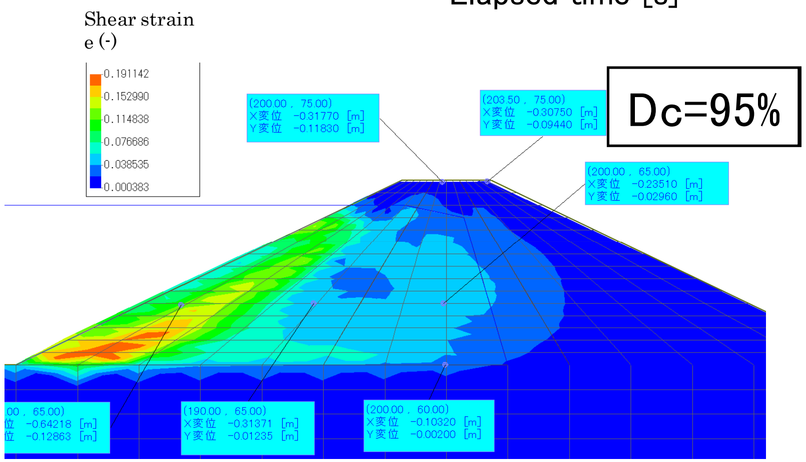
⇨ Similarly as Newmark-D, analysis realistically reproduces strong effects of compaction on the crest settlement

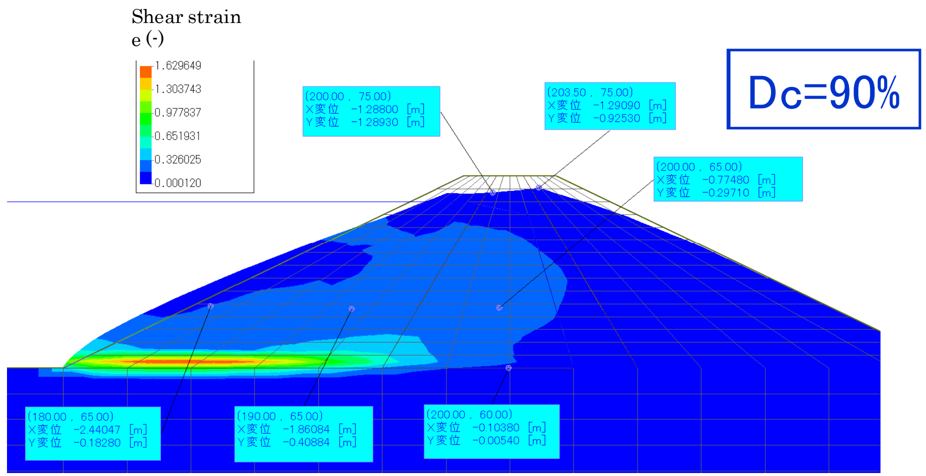
Analysis examples : effects of Dc







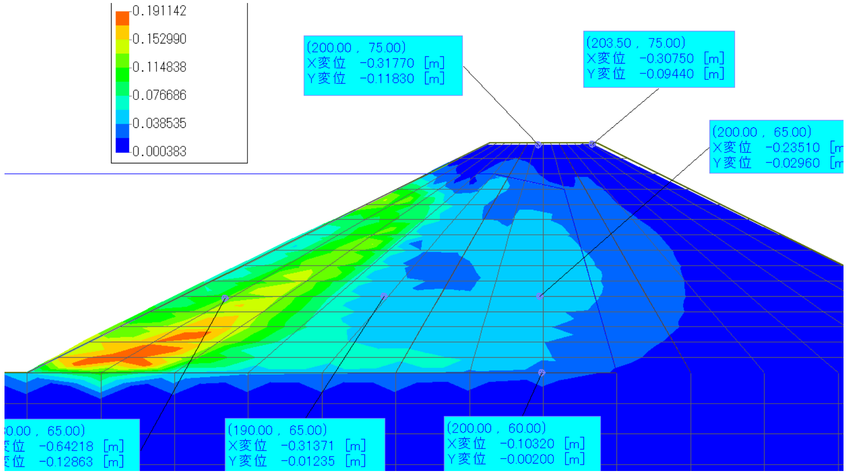


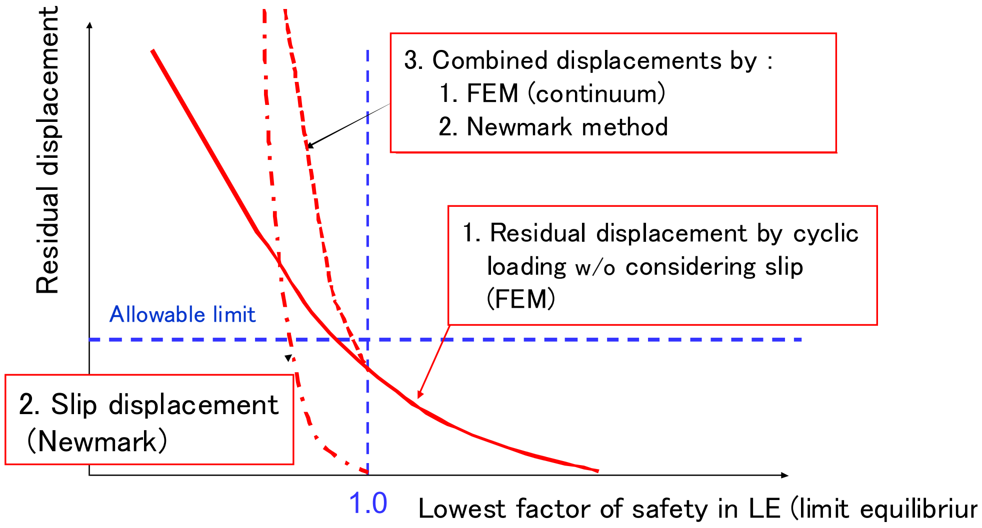


⇨ Large influence of inertia, max. settlement may be underestimated by static analyses taking into account only rigidities before/after earthquake

Combination of Newmark and Pseudo-static FEM

Pseudostatic FEM until start of sliding
t=53.12 sec.

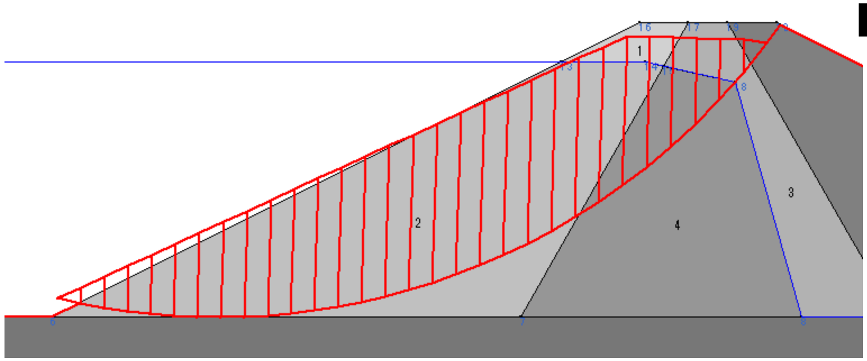




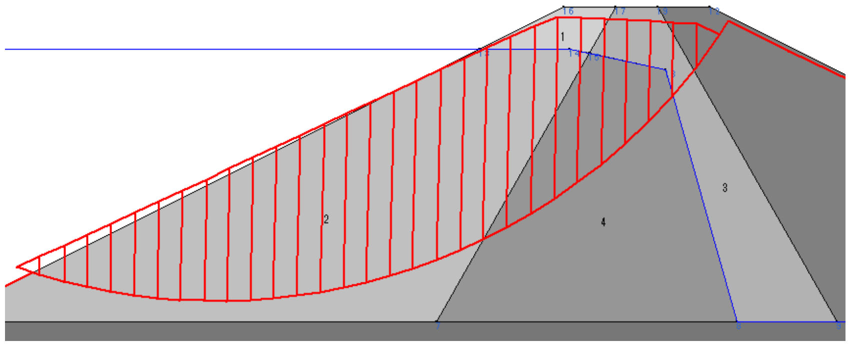
Dc=90%

⊕

Rotational displacement
by Newmark-D



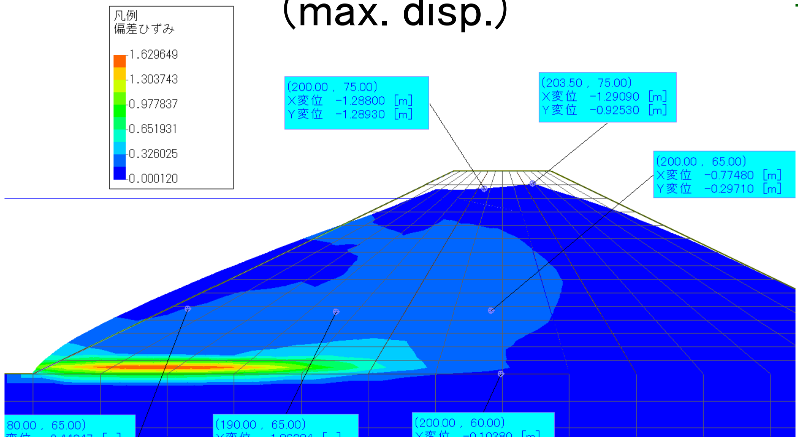
Total settlement at crest: s=57.1cm
Newmark-D : s=47.7cm
PS-FEM : s=9.4cm



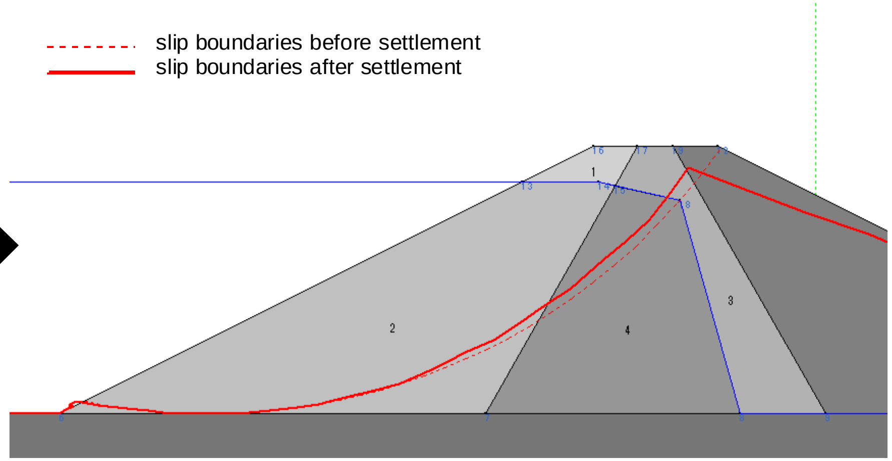
Combination of Newmark and Pseudo-static FEM

Pseudostatic FEM (max. disp.)

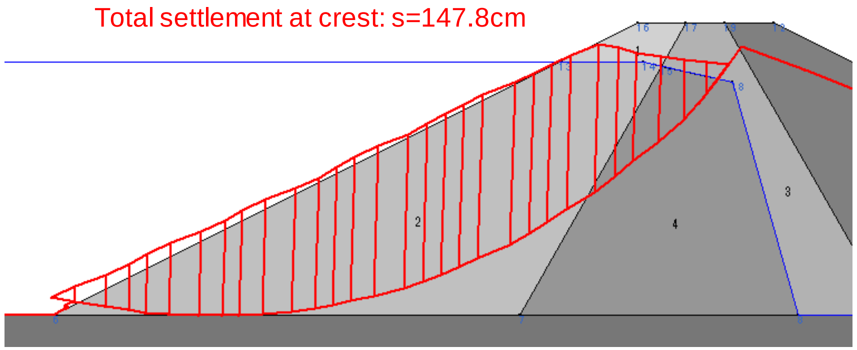
Dc=90%

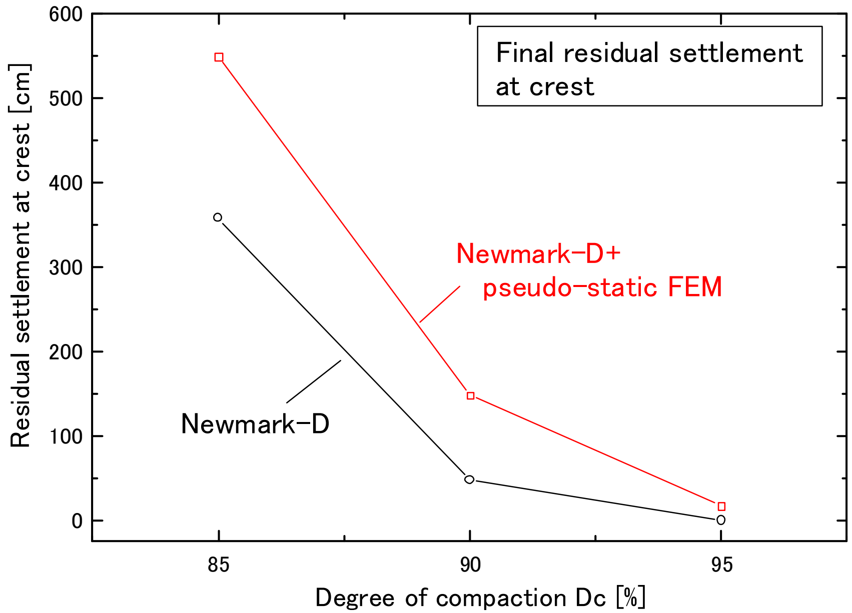


Increment from t=53.12 sec

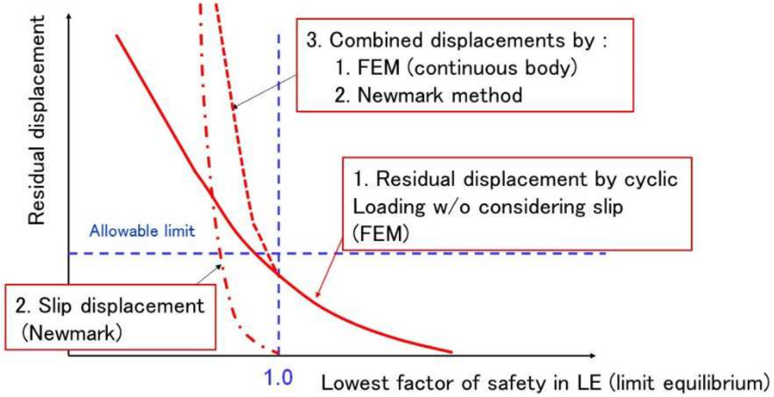


Combined deformation

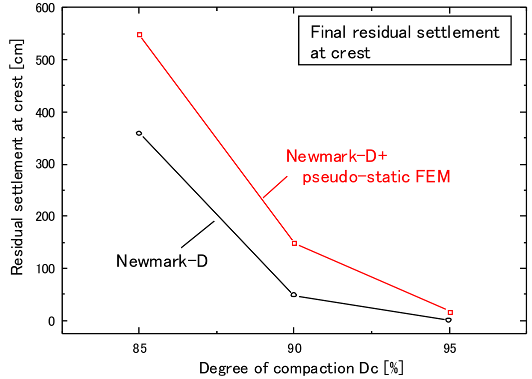




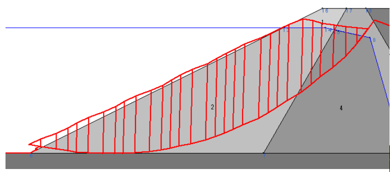
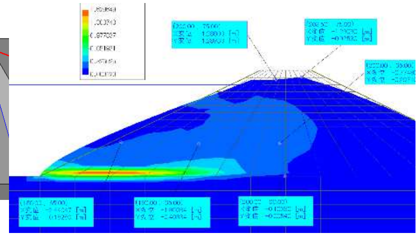
CONCLUSIONS

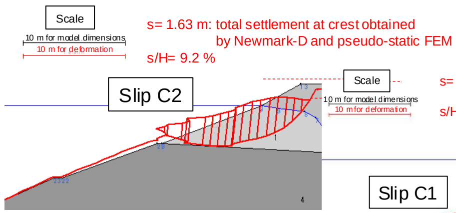


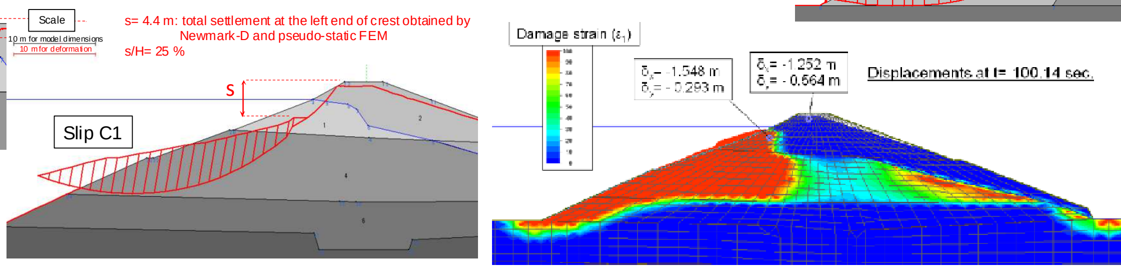
- Proposed simplified dynamic analysis: Combination of Newmark & pseudo-static FEM analyses
- Consistent framework: cumulative damage & total stress concepts allowing to model directly degradation of rigidity and strength



- Results show that analysis realistically reproduces effects of degree of compaction on the seismic stability of earth fill dams
- Results for real case study (Fujinuma dam) show good agreement with observations, constitutes first validation of the proposed analysis






THANK YOU FOR
YOUR ATTENTION