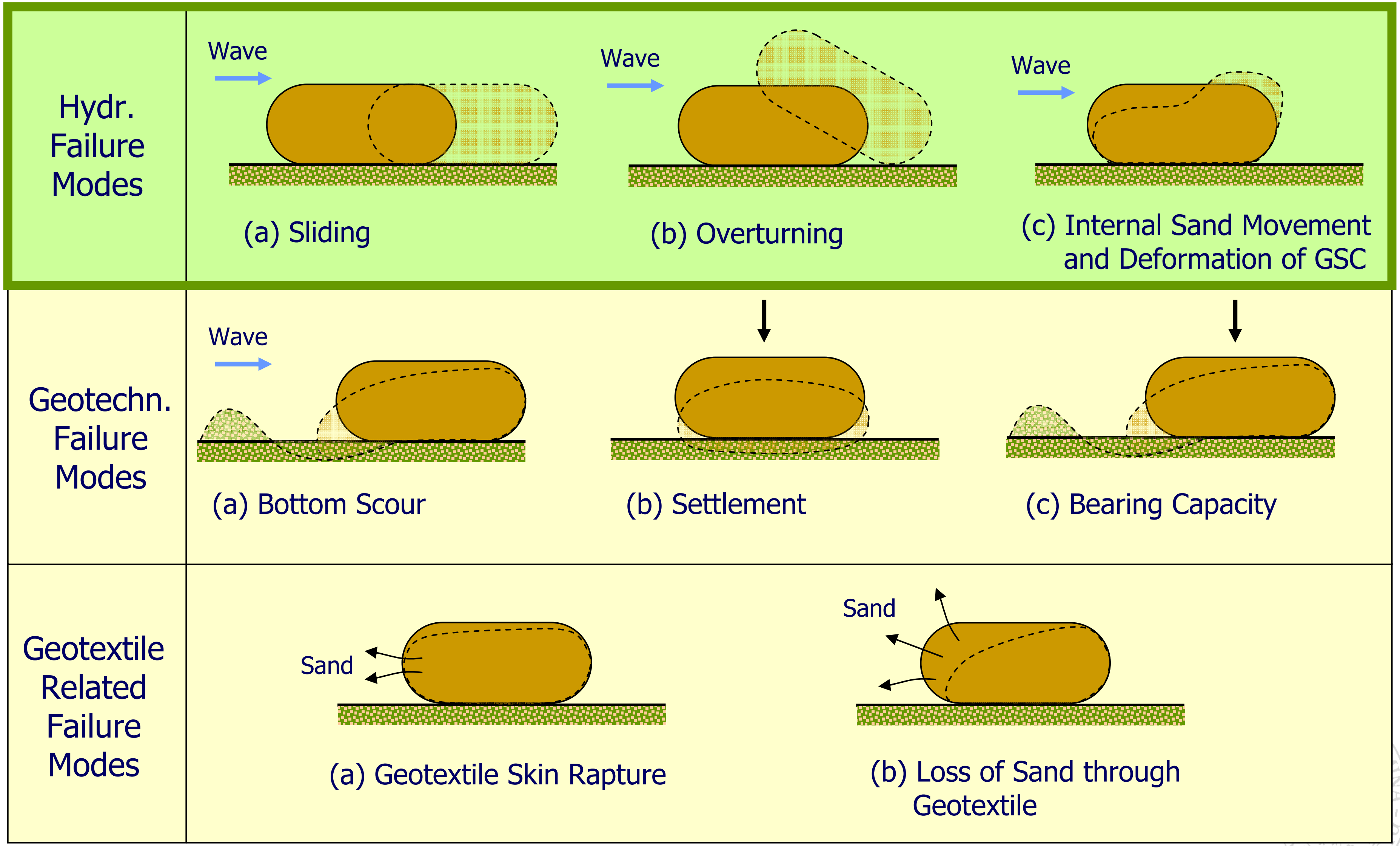
Lecture IV

Simple and Process-Based Stability Formulae and Example Calculations for GSC on the Slope and Crest of Coastal Structures

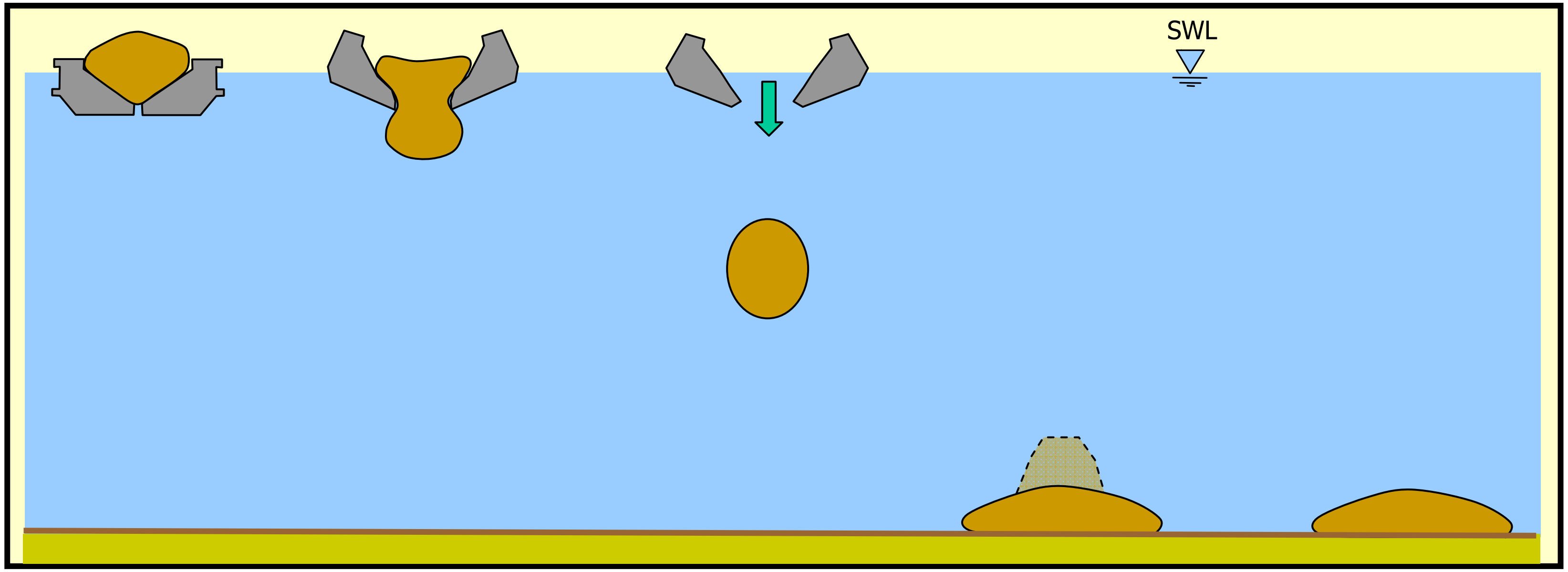
Contents of Lecture IV

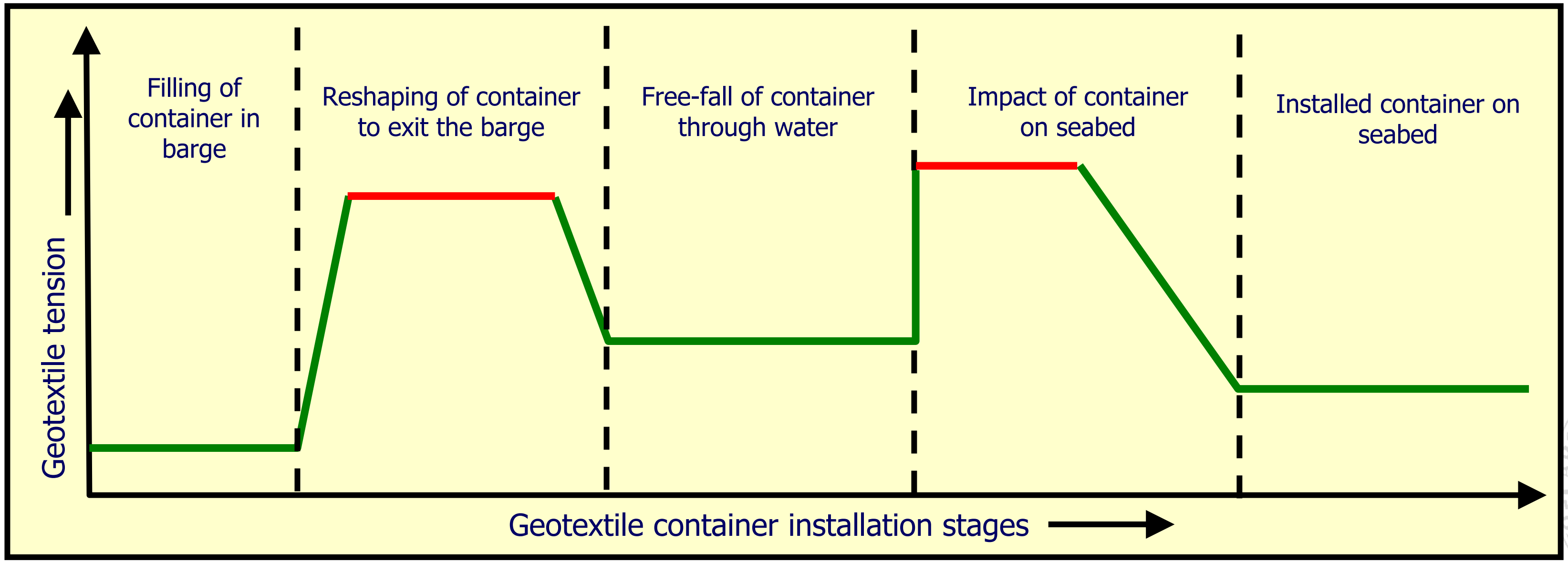
5.1 Overview of Failure Modes

Failure Modes of Geotextile Sand Containers for Coastal Protection



Loads Developed During Container Installation



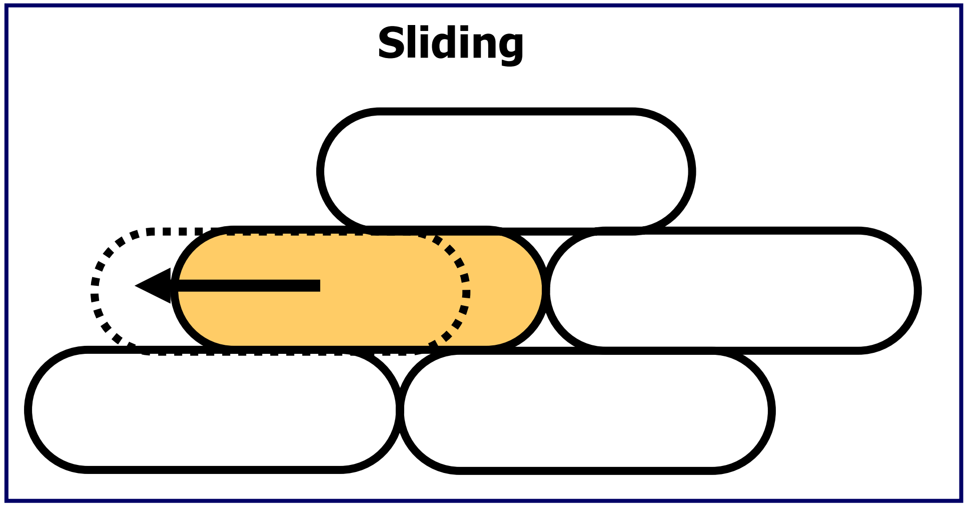


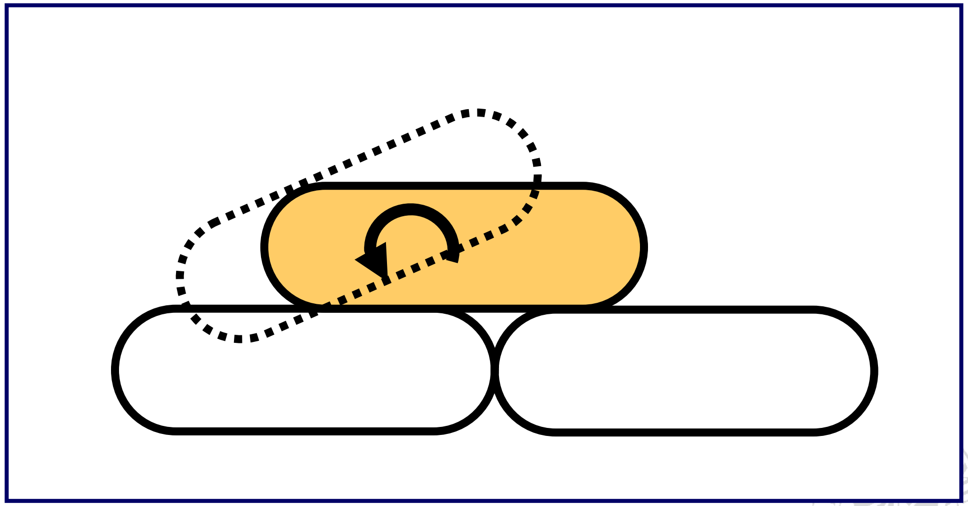
(LAWSON, 2006)

5.2 Simple HUDSON-Type Hydraulic Stability Formulae

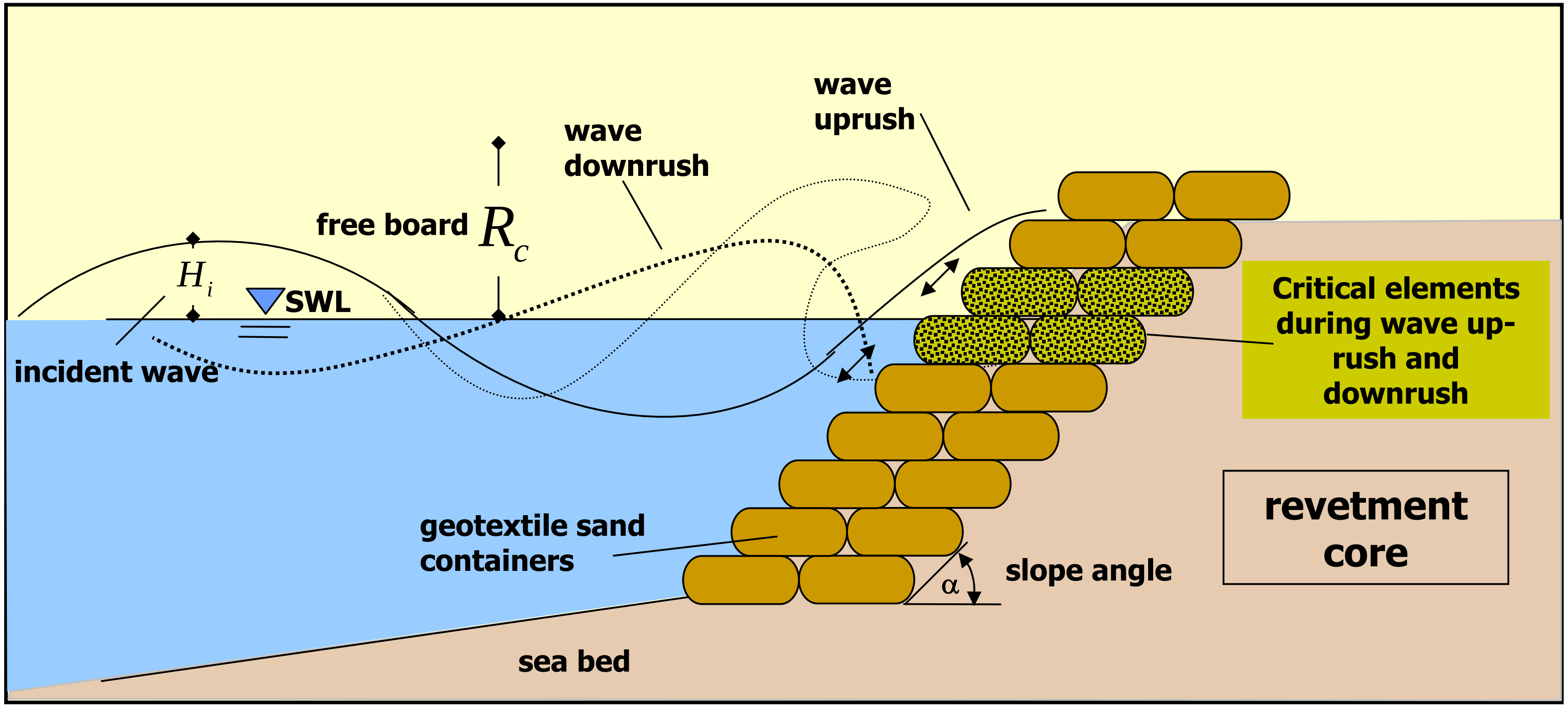
5.2.1 Hydraulic Stability of Slope Containers

Sliding and Overturning Stability





Stability of Slope Containers: Principle Sketch



Stability of Slope Containers: HUDSON-Type Equation

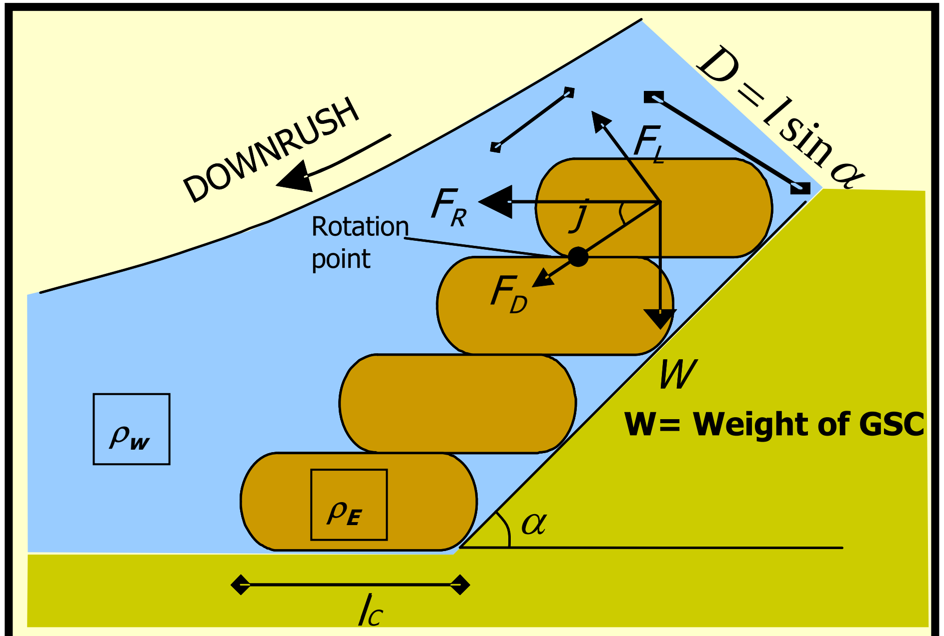
Required Weight (HUDSON):

$$W_{50} = \frac{\rho_s g H_S^{\,3}}{K\left(\frac{\rho_s}{\rho_w} - 1\right)^3 \cot\alpha}$$

Stability Number:

$$N_S = \frac{H_S}{\left(\rho_E / \rho_W - 1\right)\cdot D} = (K\cot\alpha)^{1/3}$$

$$N_S = \frac{H_S}{\left(\frac{\rho_E}{\rho_W} - 1\right)\cdot D} = \frac{C_W}{\sqrt{\xi_0}}$$



F_R= Resultant force; F_D= Drag force; F_L= Lift force

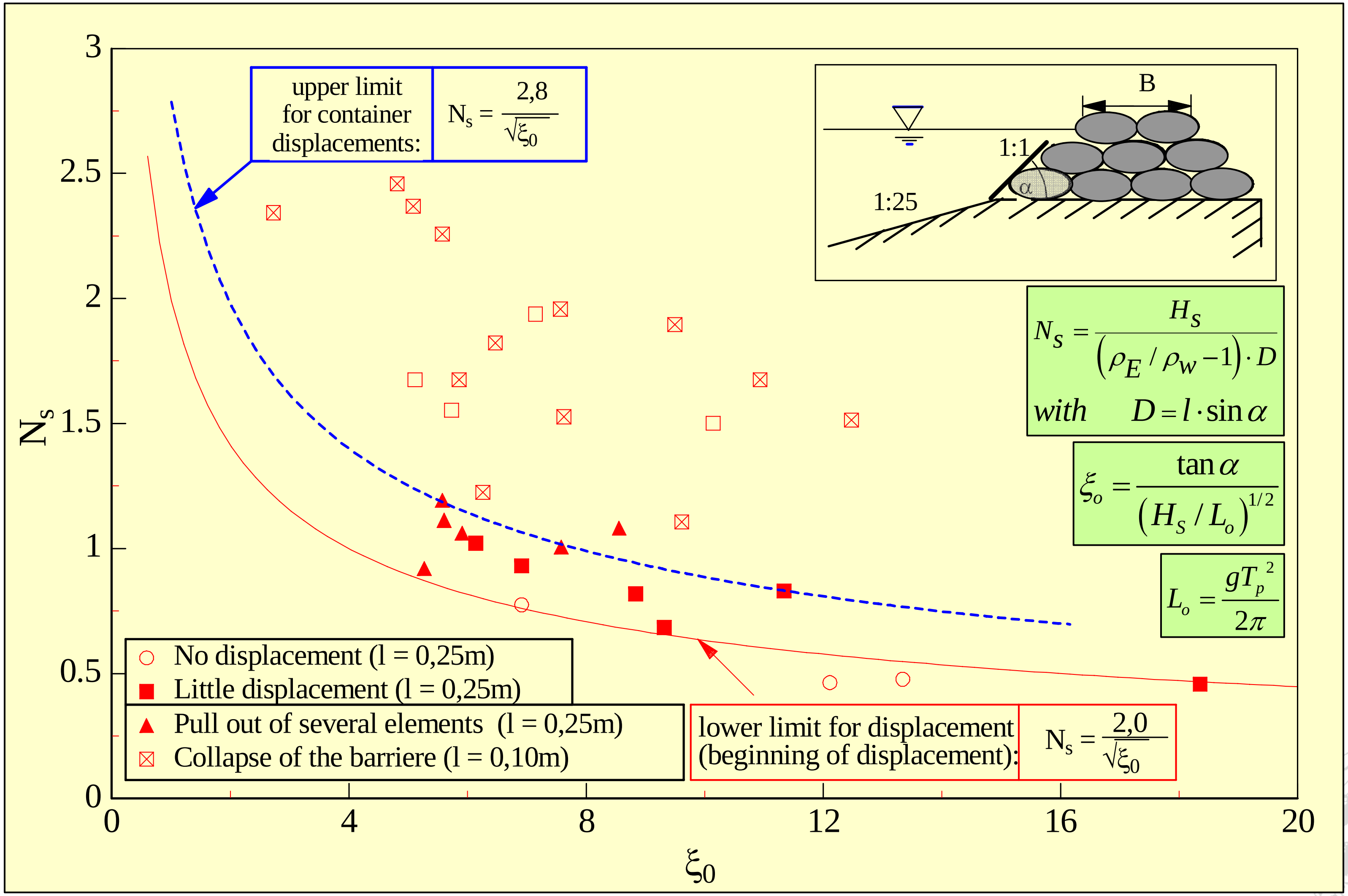
- H_S= significant wave height
- D= $l \cdot \sin\alpha$ (see Figure)
- ρ_W= water density
- ρ_E= density of GSC

  $$\rho_E = (1-n)\cdot\rho_s + \rho_w \cdot n$$

  n: the porosity of the filling material (sand)
- ρ_S= density of sand grain
- ξ_o= surf similarity parameter: $\xi_o = \tan\alpha / \sqrt{H_s / L_o}$
- C_W = empirical parameter (to be determined by scale model tests)

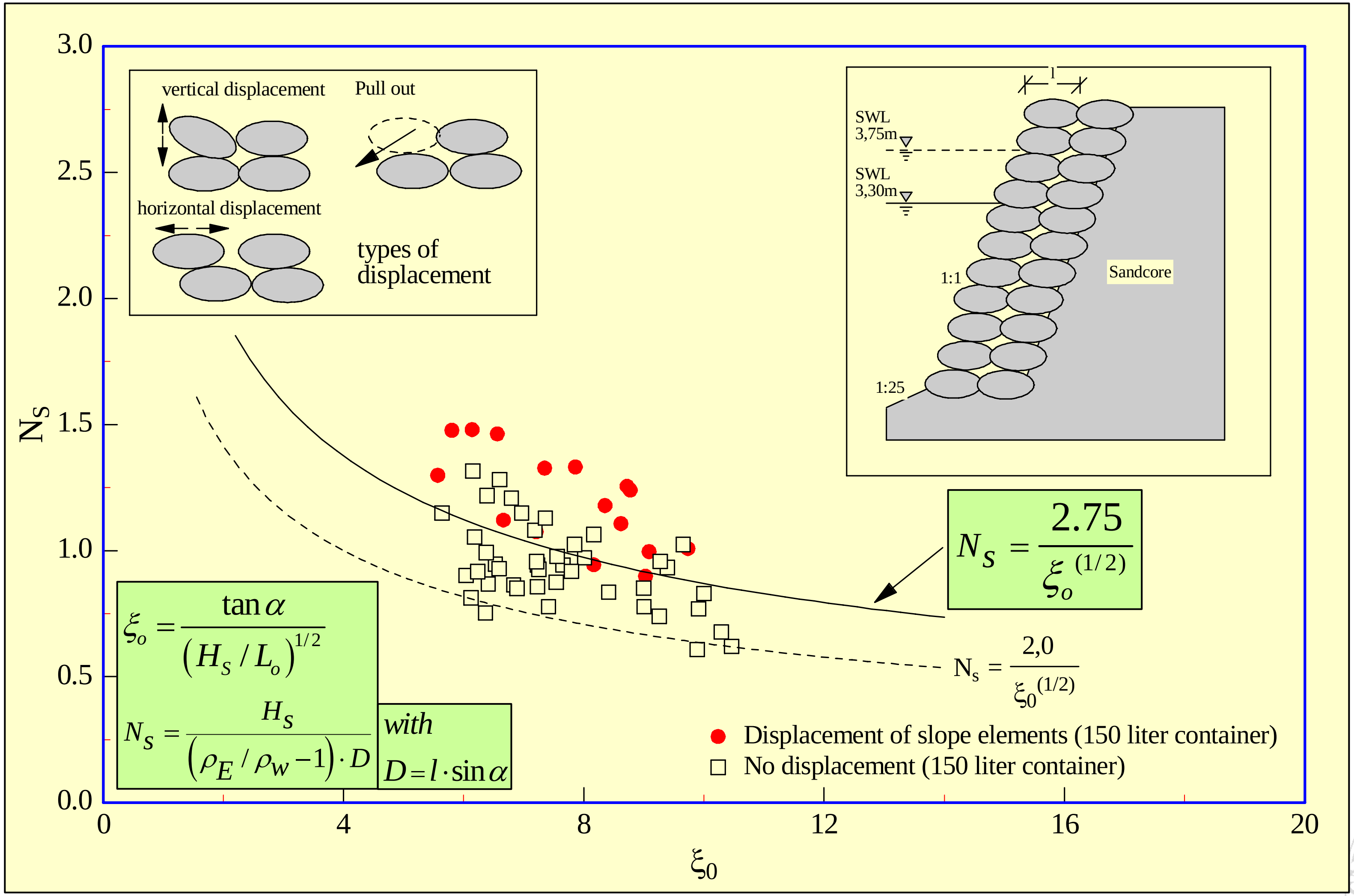
Slope Containers: Stability number N_s vs. Surf Similarity Parameter ξ_o

Result of small-scale model tests



Removed Sand Containers during Scale Model Tests at LWI

Stability of Containers on the Structure Slope (large-scale model tests)



Sand Container Removed from Structure Slope (large-scale model tests)

Design formula for length l_c of slope containers [m]

$$l_c = \frac{H_S^{3/4} \cdot \sqrt{T_p}}{1.74 \cdot \left(\frac{\rho_E}{\rho_W} - 1 \right) \cdot \sqrt{\sin(2\alpha)}}$$

with

- H_s = significant wave height [m]
- T_p = Peak period of waves [s]
- α = slope angle of structure [°]
- ρ_E = bulk density of GSC [kg/m^3]
- ρ_W = density of water [kg/m^3]

$$\rho_E = (1-n) \cdot \rho_s + \rho_w \cdot n$$ ($\rho_E \approx 1800$ kg/m³ for Sand)

- n = porosity of fill material [-]
- ρ_S = density of grain material [kg/m³] ($\rho_S \approx 2650$ kg/m³ for Quarzsand)

Required Size and Weight of Slope Containers

$$N_S = \frac{2.75}{\xi_o^{(1/2)}}$$;

Volume of GSC:

$$V = 0.065 \cdot l_c^3$$

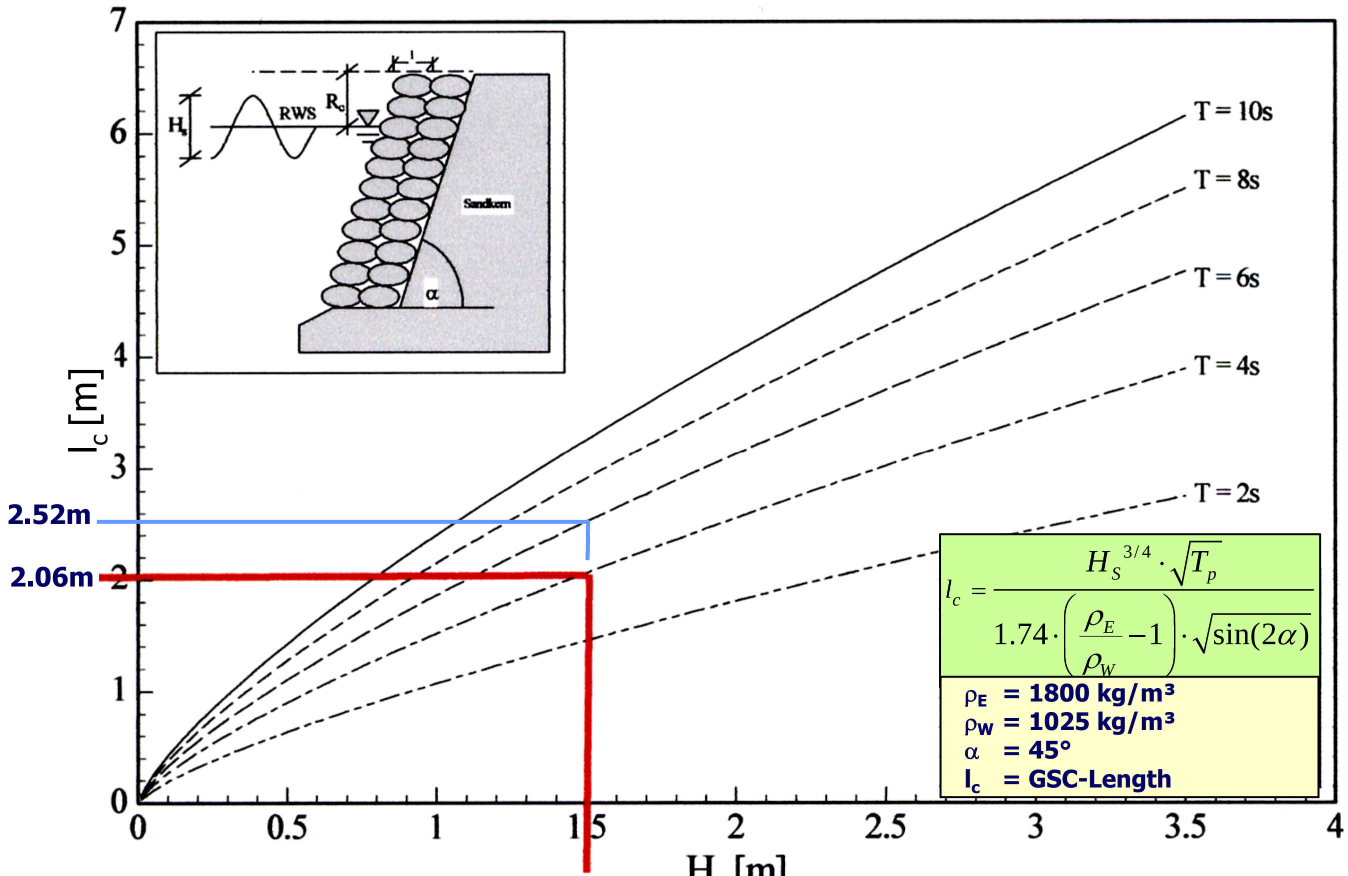
and

Density of GSC:

$$\rho_E = (1-n)\cdot\rho_s + \rho_w \cdot n$$

Required Weight of GSC:

$$W = 0.065 \cdot \rho_w \cdot l_c^3$$



$$l_c = \frac{H_S^{3/4}\cdot\sqrt{T_p}}{1.74\cdot\left(\frac{\rho_E}{\rho_W}-1\right)\cdot\sqrt{\sin(2\alpha)}}$$

ρ_E = 1800 kg/m³
ρ_W = 1025 kg/m³
α = 45°
l_c = GSC-Length

Example:

H_S= 1.5s; T_p=4.0s

⇒ l_c= 2.06m (*) ⇒ V= 0.569m³

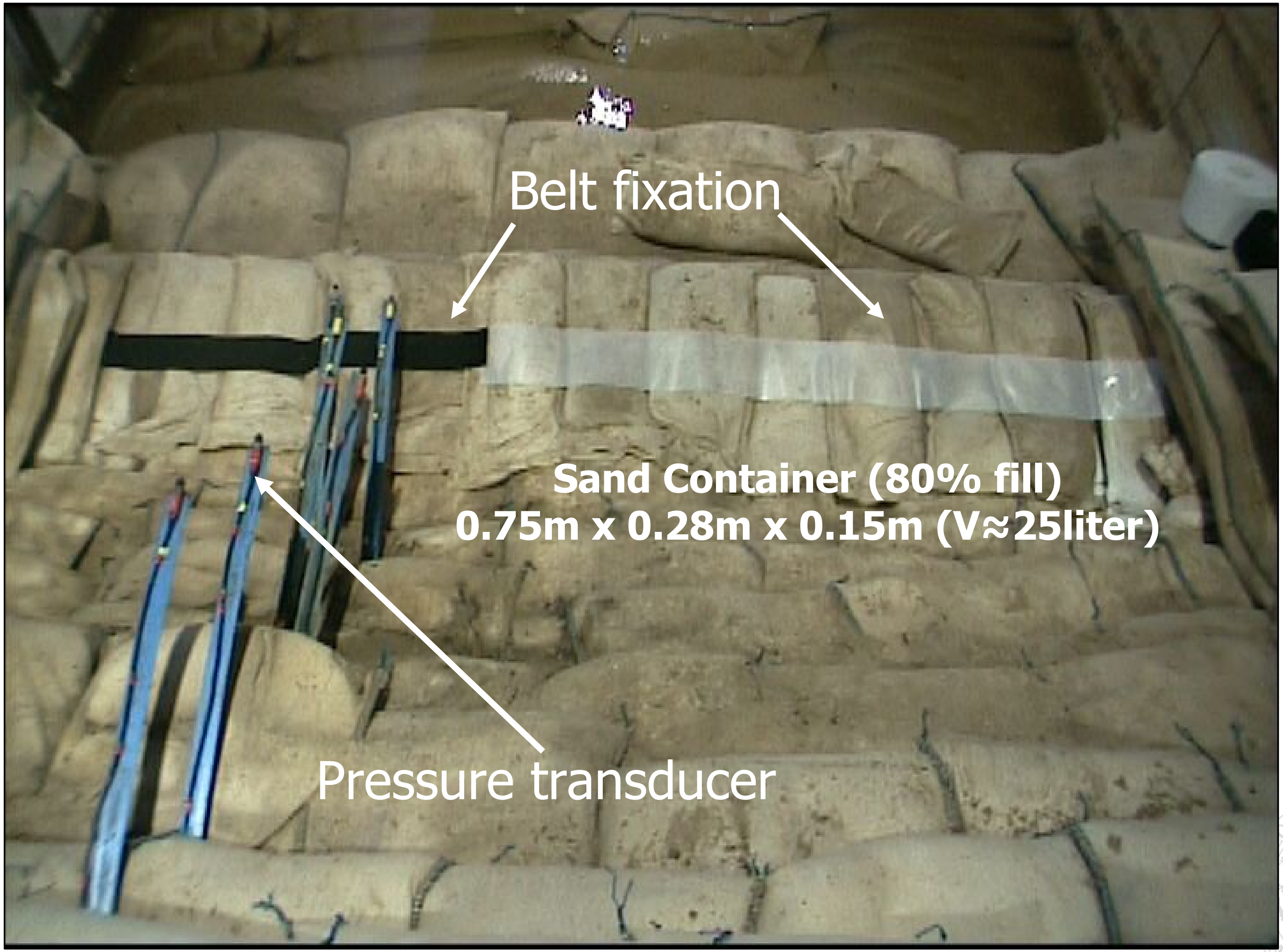
$$W \approx 10\,kN$$

For Rock (ρ_S=2700kg/m³) HUDSON Formula with k_D=2.0 will provide:

$$W = \frac{\rho_s g H_S^3}{K\left(\frac{\rho_s}{\rho_w}-1\right)^3 \cot\alpha} \approx 10KN$$

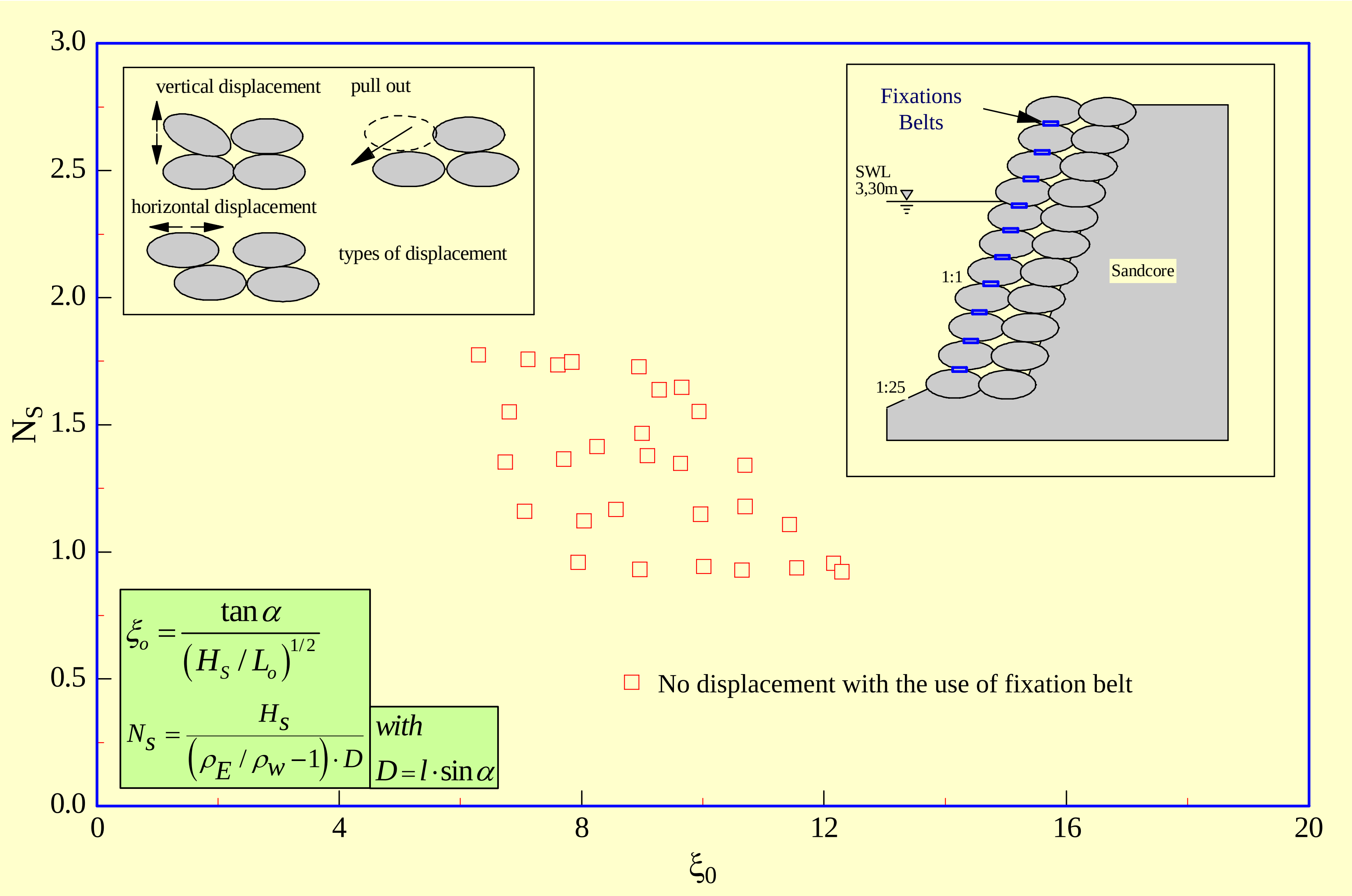
(*) Remark: For T_p= 6.0s ⇒ l_c= 2.52m and W=18kN

Model Construction Phase III (Belt Fixation) in GWK



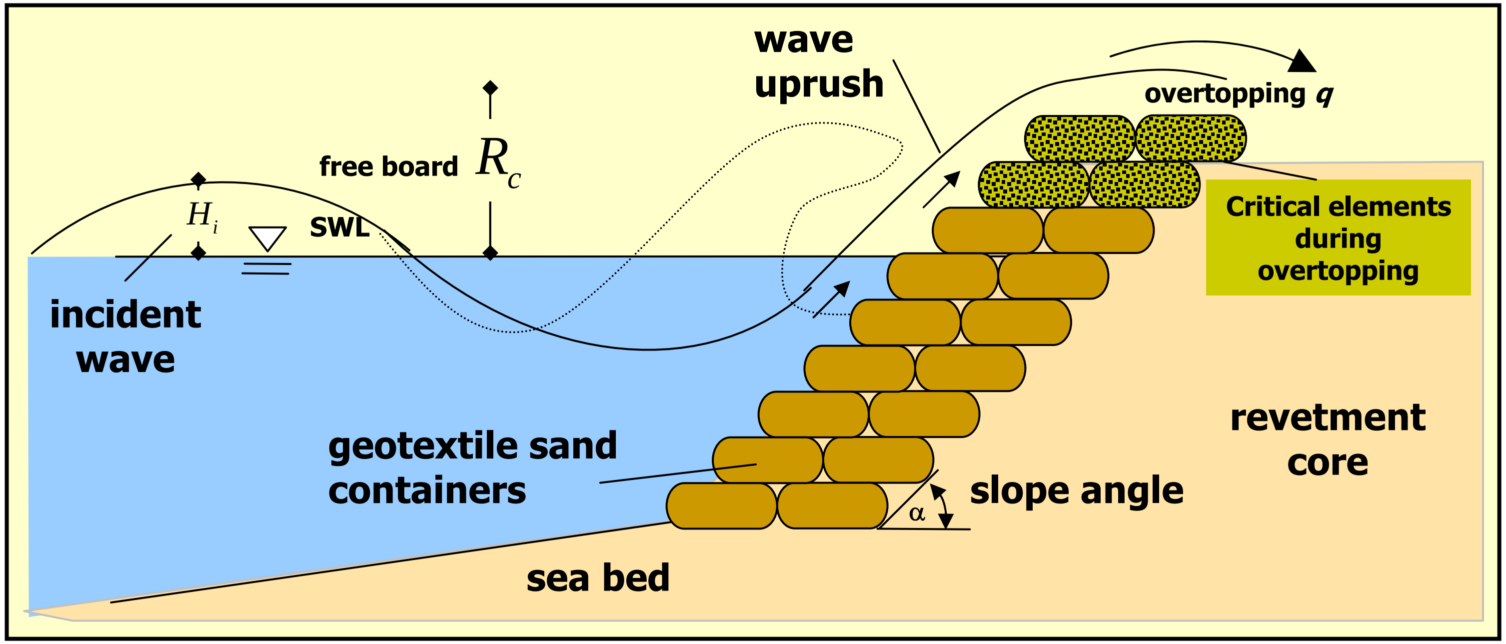
Results – Test Phase III (Fixed Elements) in GWK

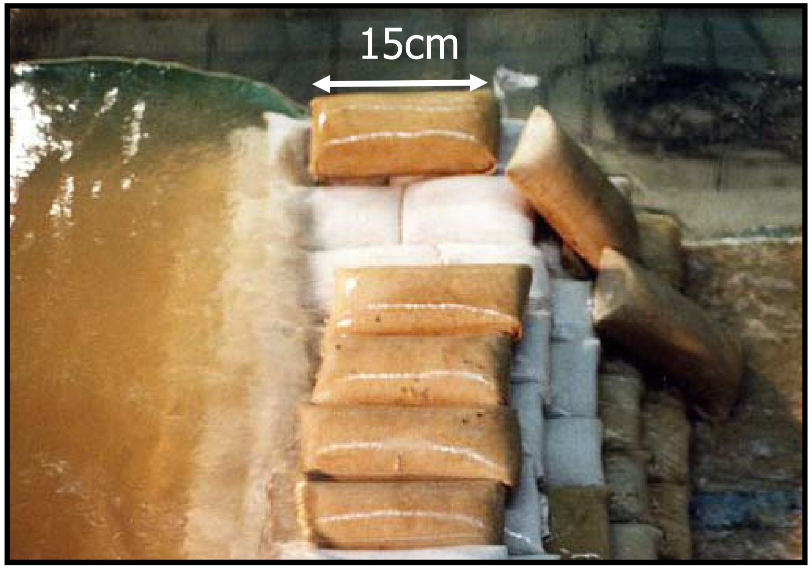
Stability number N_S of „belt fixated" Sand Containers (25 l)



5.2.2 Hydraulic Stability of Crest Containers

Stability of Crest Containers





Sliding of Crest Containers in LWI-Wave Flume.

Sand Container Removed Seaward from Crest of Structure (GWK tests)

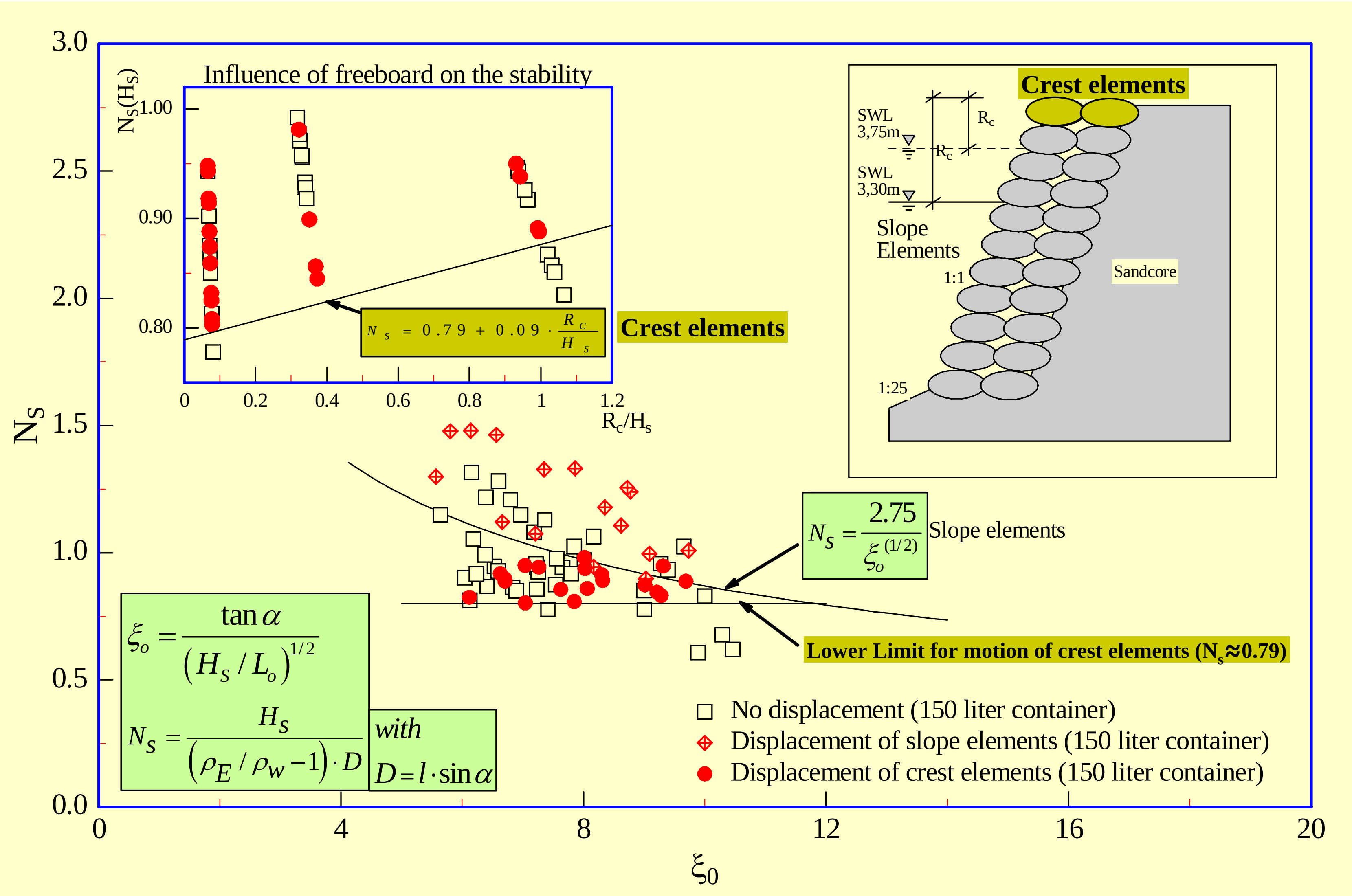
$$N_S = \frac{H_S}{\left(\rho_E / \rho_W - 1\right) \cdot D} < 0.79 + 0.09 \cdot \frac{R_C}{H_S}$$

with

R_C= freeboard [m]

D= $l_c \cdot \sin\alpha$

Stability of Sand Containers at the Crest of the Structure (large-scale model tests)



Design formula for length l_c of crest containers [m]

$$l_c = \frac{H_S}{\left(\frac{\rho_E}{\rho_W} - 1\right) \cdot \left(0.79 + 0.09 \cdot \frac{R_c}{H_S}\right) \cdot \sin\alpha}$$

with

H_s = significant wave height [m]

R_c = crest freeboard [m]

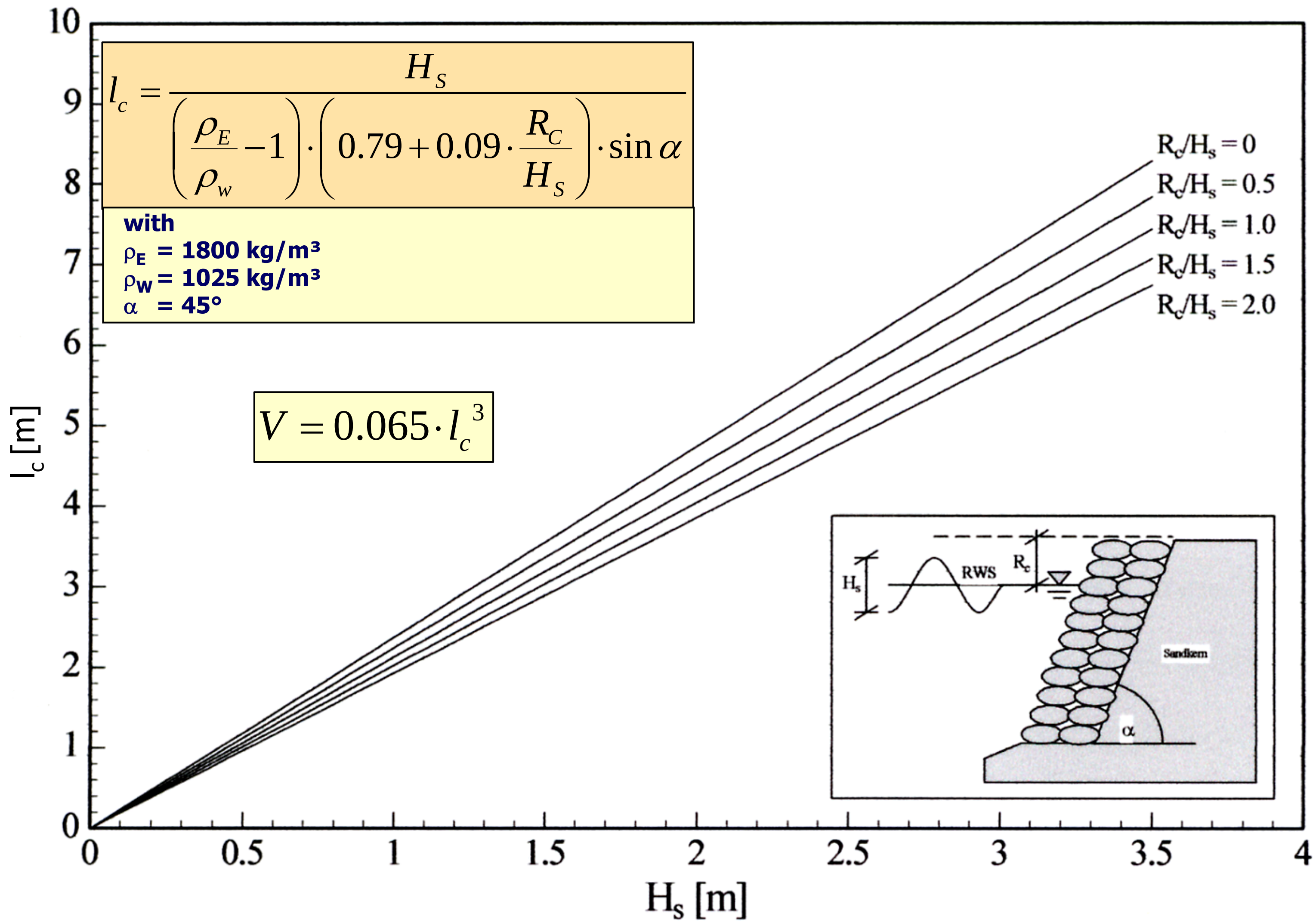
α = slope angle of structure [°]

ρ_W = density of water [kg/m³]

ρ_E = density of filling material [kg/m³]

$$\rho_E = (1-n) \cdot \rho_s + \rho_w \cdot n$$

Stability Formula for Crest Elements



$$l_c = \frac{H_S}{\left(\frac{\rho_E}{\rho_w} - 1\right) \cdot \left(0.79 + 0.09 \cdot \frac{R_C}{H_S}\right) \cdot \sin\alpha}$$

with
ρ_E = 1800 kg/m³
ρ_W = 1025 kg/m³
α = 45°

$$V = 0.065 \cdot l_c^3$$

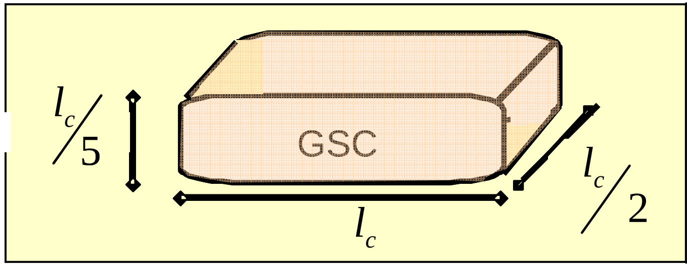
Example: H_S= 1.5s; R_C/H_S=1.2

⇒ l_c= 3.15m ⇒ V=20.3m³ ➡ $W \approx 36.6\,kN$ (more than 3.5 times larger by weight than for slope containers)

5.3 Process-Based Stability Formulae

5.3.1 Stability Formulae Without Account for Deformation Effects

Stability Against Sliding



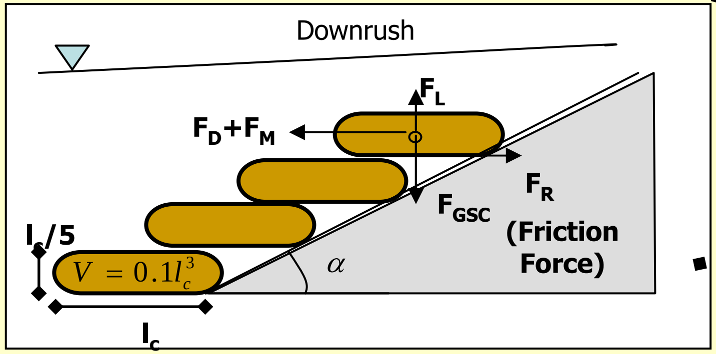
Volume

$$V = \frac{l_c^3}{10}$$

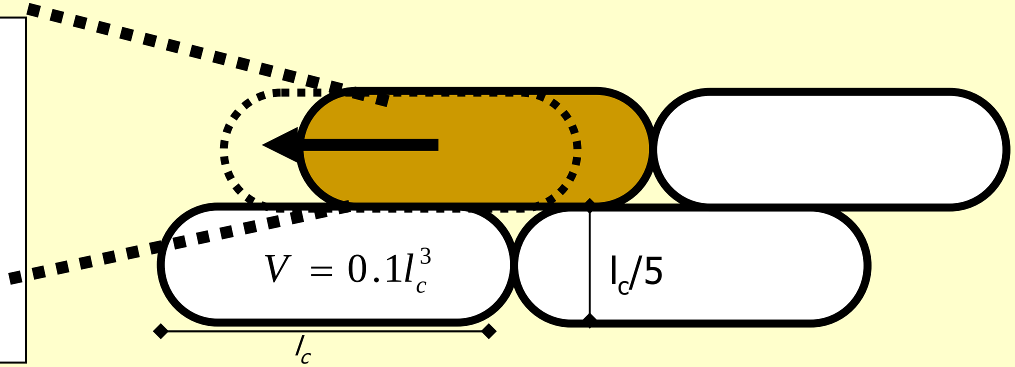
(a) Geometry of Common GSC Used for Coastal Structures

(b) Definition Sketch for Sliding Stability

(a) Forces on GSC



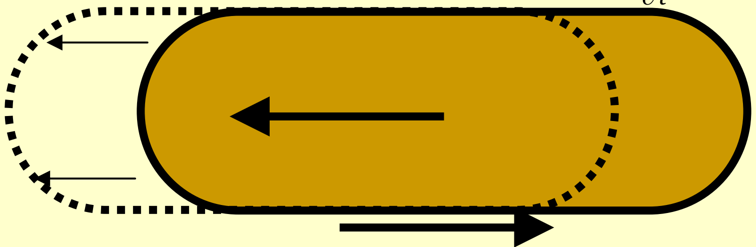
(b) Analyzed Conditions



(c) Sliding of GSC

Mobilizing force: Drag + Inertia force

$$F_D + F_M = 0.5\rho_w u^2 C_D A_s + C_M \rho_w V \frac{\partial u}{\partial t}$$



Resisting Force: Friction

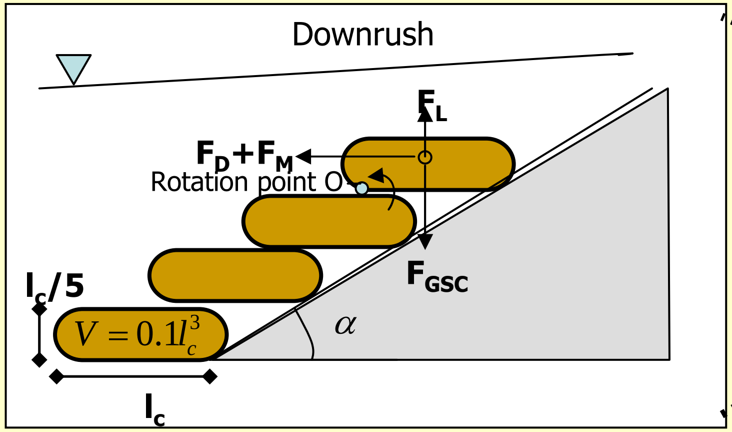
$$F_{Resisting} = \mu(F_{GSC} - F_{lift})$$

(d) Sliding Stability Formula

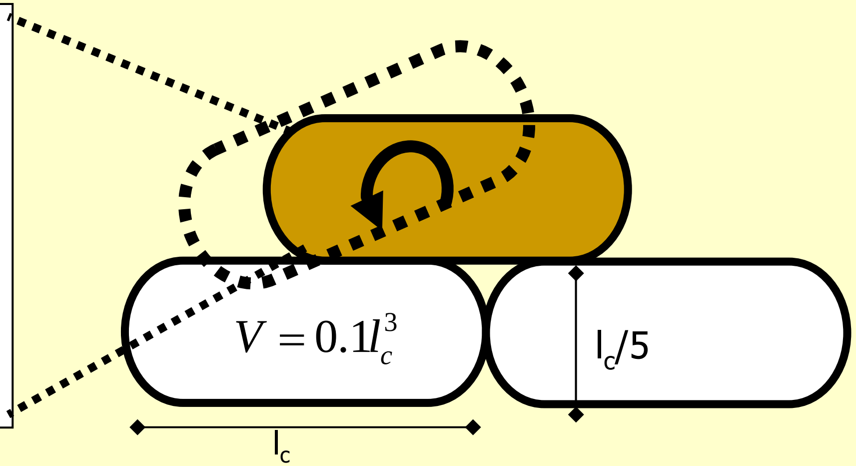
$$l_{c(sliding)} \geq u^2 \frac{[0.5C_D + 2.5C_L\mu]}{\left[\mu\Delta g - C_M \frac{\partial u}{\partial t}\right]}$$

$$W_{GSC} \geq \rho_E \left(\frac{[0.5C_D + 2.5C_L\mu]}{\left[\mu\Delta g - C_M \frac{\partial u}{\partial t}\right]}\right)^3 /10$$

(a) Forces on GSC



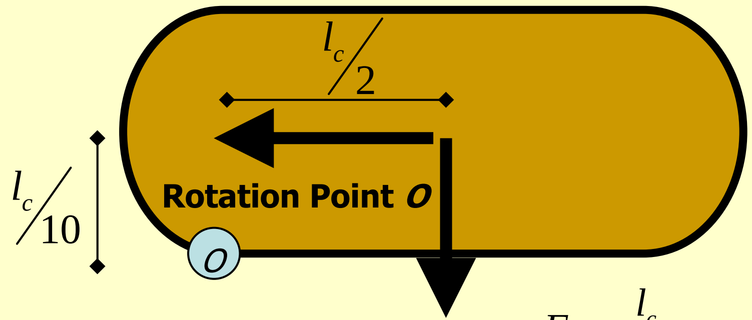
(b) Analyzed Conditions



(c) Overturning of GSC

Mobilizing Moment : Drag and Inertia induced moment

$$F_D\frac{l_c}{10}+F_M\frac{l_c}{10}+F_L\frac{l_c}{2}$$



Resisting Force: Weight moment $F_{GSC}\cdot\frac{l_c}{2}$

(d) Overturning Stability Formula

$$l_{c(overt.)}\geq u^2\frac{\left[0.05C_D+1.25C_L\right]}{\left[0.5\Delta g-0.1C_M\frac{\partial u}{\partial t}\right]}$$

$$W_{GSC}\geq\rho_E\left(\frac{\left[0.05C_D+1.25C_L\mu\right]}{\left[0.5\Delta g-0.1C_M\frac{\partial u}{\partial t}\right]}\right)^3/10$$

Definition of Parameters and Typical Values to be Used in the Stability Formulae

Definition of Parameters and Typical Values

Definition of parameters:

l_c is the required length of the container in m

W_{GSC} is the required mass of the container in kg

u is the horizontal velocity derived at the depth of the critical container in m/s

$\frac{\partial u}{\partial t}$ is the horizontal acceleration derived from the obtained velocity in m/s^2

μ is the friction factor between geotextiles

g is the gravity acceleration in m/s^2

$\Delta = \left(\frac{\rho_s}{\rho_w} - 1\right)$ *where*

ρ_E is the density of the sand fill in the GSC in kg/m^3

ρ_w is the density of the water in the GSC in kg/m^3

$Re = \left(\frac{uD}{\nu}\right)$ is the Reynolds number

D is the length scale of GSC in the flow direction $D = l_c$ in meters

ν is the kinematic viscosity of water in m^2/s

KS_i is the deformation factor for sliding

KO_i is the deformation factor for overturning

Typical values of parameters:

u and $\frac{\partial u}{\partial t}$ can be obtained from wave theories m/s in m/s^2 and respectively

$\mu = 0.57$ for non-woven geotextiles and sea bed of sand

$\mu = 0.48$ for non-woven geotextiles

g = 9.81 in m/s^2

$\Delta = 0.76$ If $\rho_E = 1800 kg/m^3$ and $\rho_w = 1025 kg/m^3$

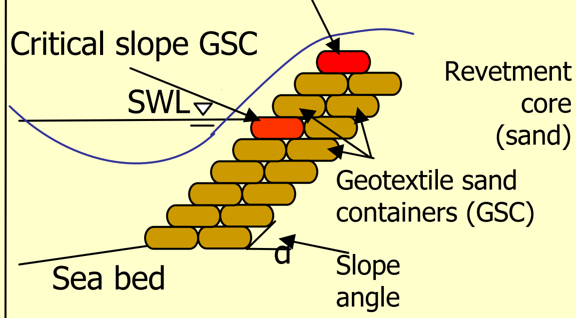
$\nu = 10^{-6} m^2/s$

Remarks and Limitations

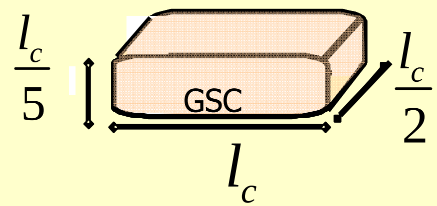
If the local Reynolds number is higher than 10^6 and/or the wave conditions do not correspond to "shallow water" conditions (d/L<0.10), the results should be interpreted with caution, since only Re<10^6 and shallow conditions were tested in this study.

The force coefficients are a function of the Reynolds number and thus of the length of the container. Calculation of the desired length is an iterative process. The length is calculated with approximate force coefficients and then the coefficients are adjusted to match the corresponding Reynolds number.

Refer to section 6.4 for more details on the validity and limitations

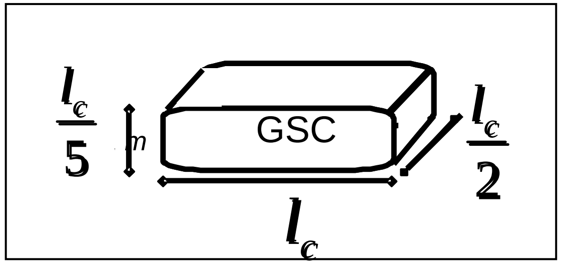


Considered Geometry



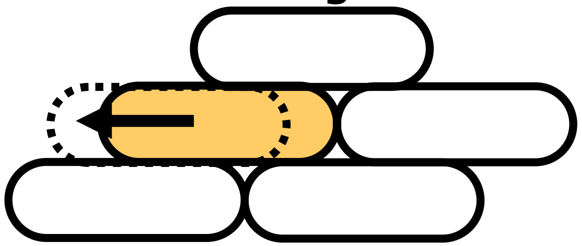
Formulae valid only for this geometry of the geotextile sand containers. However, formulae, coefficients and deformation factors can be adapted to any other geometry

5.3.2 Stability Formulae Including Deformation Effects

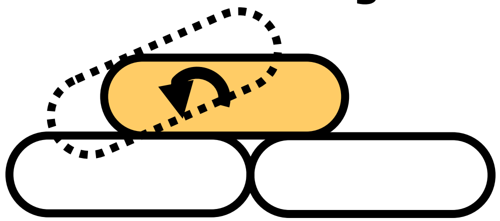


Formulae WITH Deformation Effects

Sliding



Overturnning



Sliding Formula

$$l_{c(sliding)} \geq u^2 \frac{\left[0.5K_{CD}C_D + 2.5C_L K_{CL}\mu\right]}{\left[\mu \Delta K_R g - C_M K_{CM} \frac{\partial u}{\partial t}\right]}$$

Overturning Formula

$$l_{c(overt.)} \geq u^2 \frac{\left[0.05K_{CD}C_D + 1.25K_{CL}C_L\right]}{\left[0.5\Delta K_R g - 0.1C_M K_{CM} \frac{\partial u}{\partial t}\right]}$$

K_i — **Factors that account for the deformations and the influence of neighboring sand containers**

C_i — **Drag, Inertia and Lift coefficients that were obtained from specially designed model tests**

Stability Formulae for GSCs Including the Effect of Deformation

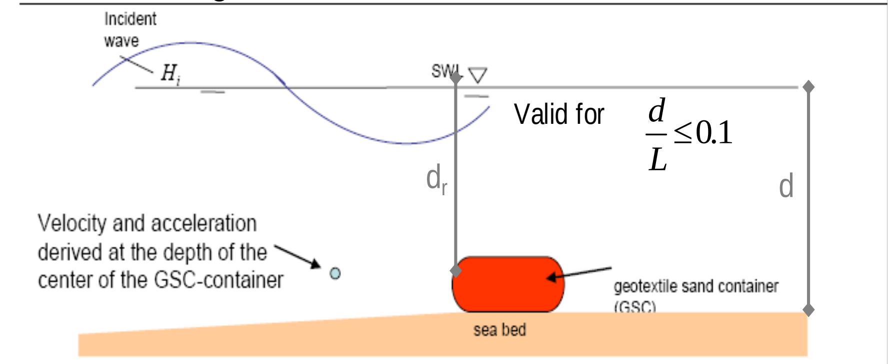
	Sliding		Overturning
Required container length	$l_{c(sl)} \geq u^2 \dfrac{\left[0.5KS_{CD}C_D + 2.5KS_{CL}C_L\mu\right]}{\left[\mu KS_R\Delta g - KS_{CM}C_M\dfrac{\partial u}{\partial t}\right]}$	Required container length	$l_{c(ov)} \geq u^2 \dfrac{\left[0.05KO_{CD}C_D + 1.25KO_{CL}C_L\right]}{\left[0.5\Delta KO_R g - 0.1KO_{CM}C_M\dfrac{\partial u}{\partial t}\right]}$
Required container mass	$W_{GSC} \geq \rho_E \left(u^2 \dfrac{\left[0.5KS_{CD}C_D + 2.5KS_{CL}C_L\mu\right]}{\left[\mu\Delta KS_R g - KS_{CM}C_M\dfrac{\partial u}{\partial t}\right]}\right)^3 /10$	Required container mass	$W_{GSC} \geq \rho_E \left(u^2 \dfrac{\left[0.05KO_{CD}C_D + 1.25KO_{CL}C_L\right]}{\left[0.5\Delta KO_R g - 0.1KO_{CM}C_M\dfrac{\partial u}{\partial t}\right]}\right)^3 /10$

KS_{CD}, KS_{CL}, KS_{CM} and KS_R = Deformation factors for the drag force, lift force, inertia force and resisting forces associated with sliding stability

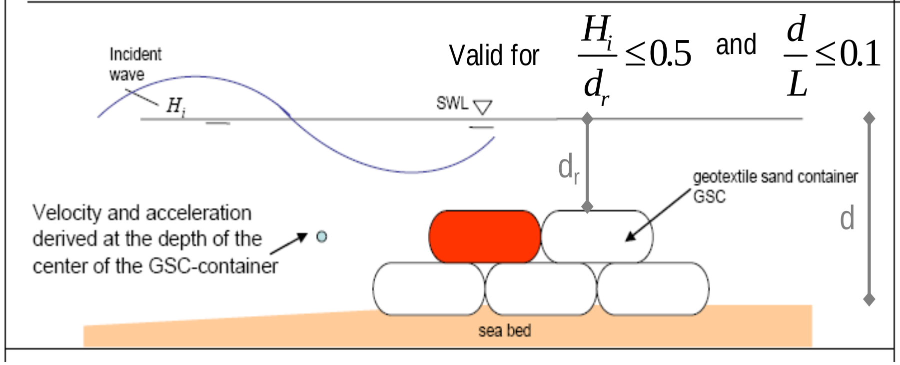
KO_{CD}, KO_{CL}, KO_{CM} and KO_R = Deformation factors for the drag force, lift force, inertia force and resisting forces associated with overturning stability

Type of Structures Made of GSC

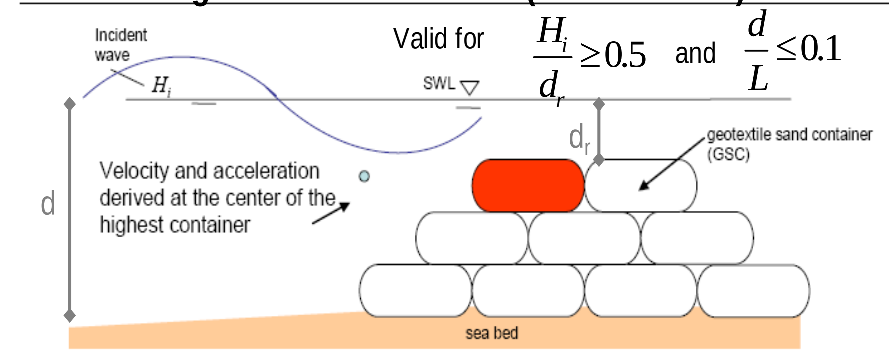
Single GSC on Sea Bed



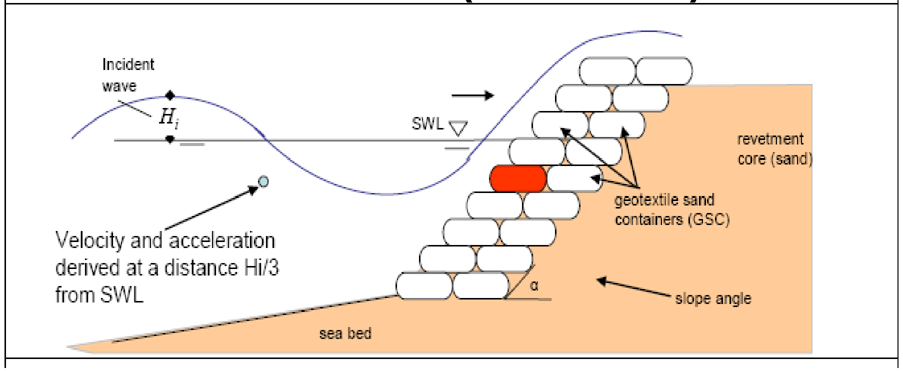
Group of GSCs on Sea Bed (i. e. Scour Protection)



Submerged GSC-Breakwaters (Artificial Reef)

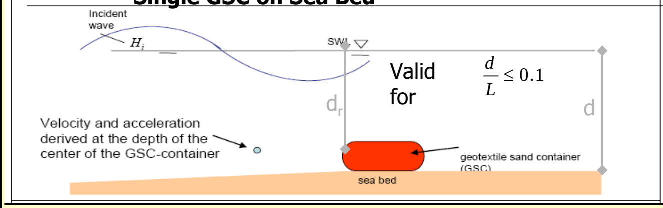
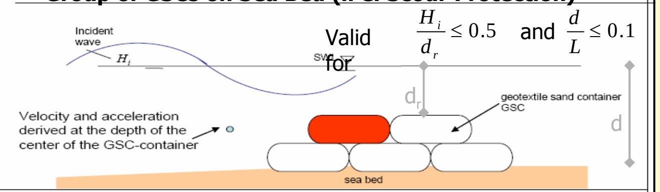
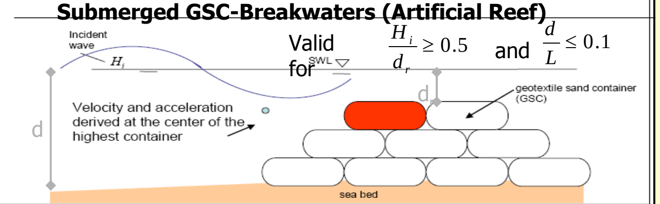
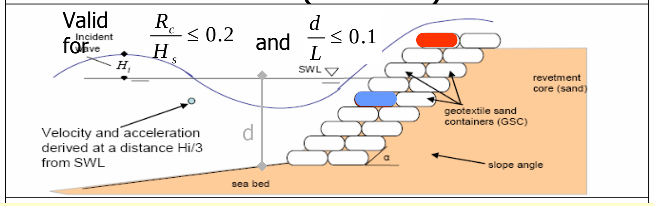
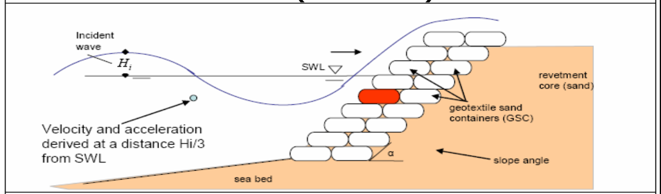


GSC- Revetments (SLOPE GSC)



5.3.3 Force Coefficients and Deformation Factors

Deformation Factors and Force Coefficients (slope angle 45° and sand fill ratio of GSC of 80%

GSC-Structure	Sliding	Overturning	Force Coefficients
Single GSC on Sea Bed  Valid for $\frac{d}{L} \le 0.1$	$KS_{CD} = 1.40$ $KS_{CM} = 1.00$ $KS_{CL} = 0.94$ $KS_R = 0.70$	$KO_{CD} = 1.54$ $KO_{CM} = 1.1$ $KO_{CL} = 0.80$ $KO_R = 0.92$	$C_D = -2x10^{-5}\,\mathrm{Re} + 6.81$ with $1.3 \le C_D \le 6.5$ $C_M = 0.60$ $C_L = 1x10^{-5}\,\mathrm{Re} - 0.612$ with $0.2 \le C_L \le 1.4$
Group of GSCs on Sea Bed (i. e. Scour Protection)  Valid for $\frac{H_i}{d_r} \le 0.5$ and $\frac{d}{L} \le 0.1$	$KS_{CD} = 1.40$ $KS_{CM} = 1.00$ $KS_{CL} = 0.94$ $KS_R = 0.70$	$KO_{CD} = 1.54$ $KO_{CM} = 1.1$ $KO_{CL} = 0.80$ $KO_R = 0.92$	$C_D = -6x10^{-5}\,\mathrm{Re} + 14.70$ with $4 \le C_D \le 11$ $C_M = 0.50$ $C_L = 1x10^{-5}\,\mathrm{Re} - 0.669$ with $0.4 \le C_L \le 1.3$
Submerged GSC-Breakwaters (Artificial Reef)  Valid for $\frac{H_i}{d_r} \ge 0.5$ and $\frac{d}{L} \le 0.1$	$KS_{CD} = 1.40$ $KS_{CM} = 1.00$ $KS_{CL} = 0.94$ $KS_R = 0.70$	$KO_{CD} = 1.54$ $KO_{CM} = 1.1$ $KO_{CL} = 0.80$ $KO_R = 0.92$	$C_D = -9x10^{-5}\,\mathrm{Re} + 23.04$ with $4 \le C_D \le 15$ $C_M = 0.30$ $C_L = 1x10^{-5}\,\mathrm{Re} - 0.587$ with $0.3 \le C_L \le 1.2$
GSC- Revetments (CREST GSC)  Valid for $\frac{R_c}{H_s} \le 0.2$ and $\frac{d}{L} \le 0.1$	$KS_{CD} = 1.40$ $KS_{CM} = 1.00$ $KS_{CL} = 0.94$ $KS_R = 0.70$	$KO_{CD} = 1.54$ $KO_{CM} = 1.1$ $KO_{CL} = 0.80$ $KO_R = 0.92$	$C_D = -2x10^{-5}\,\mathrm{Re} + 6.81$ with $1.3 \le C_D \le 6.5$ $C_M = 0.60$ $C_L = 1x10^{-5}\,\mathrm{Re} - 0.612$ with $0.2 \le C_L \le 1.4$
GSC- Revetments (SLOPE GSC) 	$KS_{CD} = 1.40$ $KS_{CM} = 1.00$ $KS_{CL} = 0.94$ $KS_R = 1.60$	Not applicable (GSC pulled out seaward)	$C_D = -3x10^{-5}\,\mathrm{Re} + 8.9$ with $2.5 \le C_D \le 9$ $C_M = 0.30$ $C_L = 1x10^{-5}\,\mathrm{Re} - 0.587$ with $0.3 \le C_L \le 1.2$

Force Coefficients and Deformation Factors for Stability Formulae

(a) Stability Formulae for GSCs Including the Effect of Deformation

Sliding

Required container length

$$l_{c(sl)} \ge u^2 \frac{\left[0.5KS_{CD}C_D + 2.5KS_{CL}C_L\mu\right]}{\left[\mu KS_R\Delta g - KS_{CM}C_M \frac{\partial u}{\partial t}\right]}$$

Required container mass

$$W_{GSC} \ge \rho_s \left(u^2 \frac{\left[0.5KS_{CD}C_D + 2.5KS_{CL}C_L\mu\right]}{\left[\mu \Delta KS_R g - KS_{CM}C_M \frac{\partial u}{\partial t}\right]} \right)^3 /10$$

Overturning

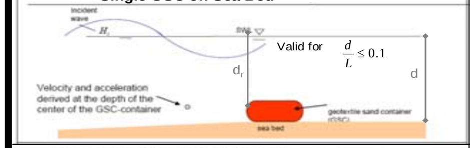
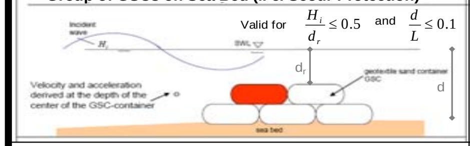
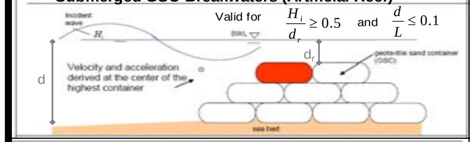
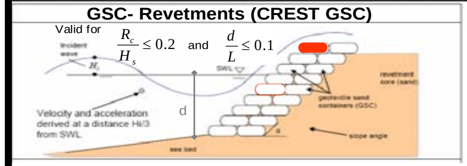
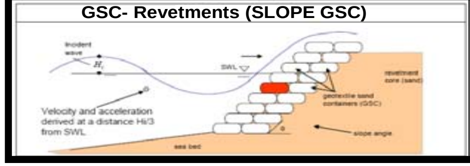
Required container length

$$l_{c(ov)} \ge u^2 \frac{\left[0.05KO_{CD}C_D + 1.25KO_{CL}C_L\right]}{\left[0.5\Delta KO_R g - 0.1KO_{CM}C_M \frac{\partial u}{\partial t}\right]}$$

Required container mass

$$W_{GSC} \ge \rho_s \left(u^2 \frac{\left[0.05KO_{CD}C_D + 1.25KO_{CL}C_L\right]}{\left[0.5\Delta KO_R g - 0.1KO_{CM}C_M \frac{\partial u}{\partial t}\right]} \right)^3 /10$$

(b) Deformation Factors and Force Coefficients for the Stability Formulae

GSC-Structure	Sliding	Overturning	Force Coefficients
Single GSC on Sea Bed 	$KS_{CD}=1.40$ $KS_{CM}=1.00$ $KS_{CL}=0.94$ $KS_R=0.70$	$KO_{CD}=1.54$ $KO_{CM}=1.1$ $KO_{CL}=0.80$ $KO_R=0.92$	$C_D=-2x10^{-5}\,Re+6.81$ with $1.3\le C_D\le 6.5$ $C_M=0.60$ $C_L=1x10^{-5}\,Re-0.612$ with $0.2\le C_L\le 1.4$
Group of GSCs on Sea Bed (i. e. Scour Protection) 	$KS_{CD}=1.40$ $KS_{CM}=1.00$ $KS_{CL}=0.94$ $KS_R=0.70$	$KO_{CD}=1.54$ $KO_{CM}=1.1$ $KO_{CL}=0.80$ $KO_R=0.92$	$C_D=-6x10^{-5}\,Re+14.70$ with $4\le C_D\le 11$ $C_M=0.50$ $C_L=1x10^{-5}\,Re-0.669$ with $0.4\le C_L\le 1.3$
Submerged GSC-Breakwaters (Artificial Reef) 	$KS_{CD}=1.40$ $KS_{CM}=1.00$ $KS_{CL}=0.94$ $KS_R=0.70$	$KO_{CD}=1.54$ $KO_{CM}=1.1$ $KO_{CL}=0.80$ $KO_R=0.92$	$C_D=-9x10^{-5}\,Re+23.04$ with $4\le C_D\le 15$ $C_M=0.30$ $C_L=1x10^{-5}\,Re-0.587$ with $0.3\le C_L\le 1.2$
GSC- Revetments (CREST GSC) 	$KS_{CD}=1.40$ $KS_{CM}=1.00$ $KS_{CL}=0.94$ $KS_R=0.70$	$KO_{CD}=1.54$ $KO_{CM}=1.1$ $KO_{CL}=0.80$ $KO_R=0.92$	$C_D=-2x10^{-5}\,Re+6.81$ with $1.3\le C_D\le 6.5$ $C_M=0.60$ $C_L=1x10^{-5}\,Re-0.612$ with $0.2\le C_L\le 1.4$
GSC- Revetments (SLOPE GSC) 	$KS_{CD}=1.40$ $KS_{CM}=1.00$ $KS_{CL}=0.94$ $KS_R=1.60$	Not applicable (GSC pulled out seaward)	$C_D=-3x10^{-5}\,Re+8.9$ with $2.5\le C_D\le 9$ $C_M=0.30$ $C_L=1x10^{-5}\,Re-0.587$ with $0.3\le C_L\le 1.2$

SIMPLE FORMULA FOR THE STABILITY OF GSC

Definition of parameters:

l_c is the required length of the container in m

W_{GSC} is the required mass of the container in kg

u is the horizontal velocity derived at the depth of the critical container in m/s

$\frac{\partial u}{\partial t}$ is the horizontal acceleration derived from the obtained velocity in m/s^2

μ is the friction factor between geotextiles

g is the gravity acceleration in m/s^2

$$\Delta = \left(\frac{\rho_s}{\rho_w} - 1\right) \quad \textit{where}$$

ρ_S is the density of the sand fill in the GSC in kg/m^3

ρ_w is the density of the water in the GSC in kg/m^3

$$Re = \left(\frac{uD}{\nu}\right)$$ is the Reynolds number

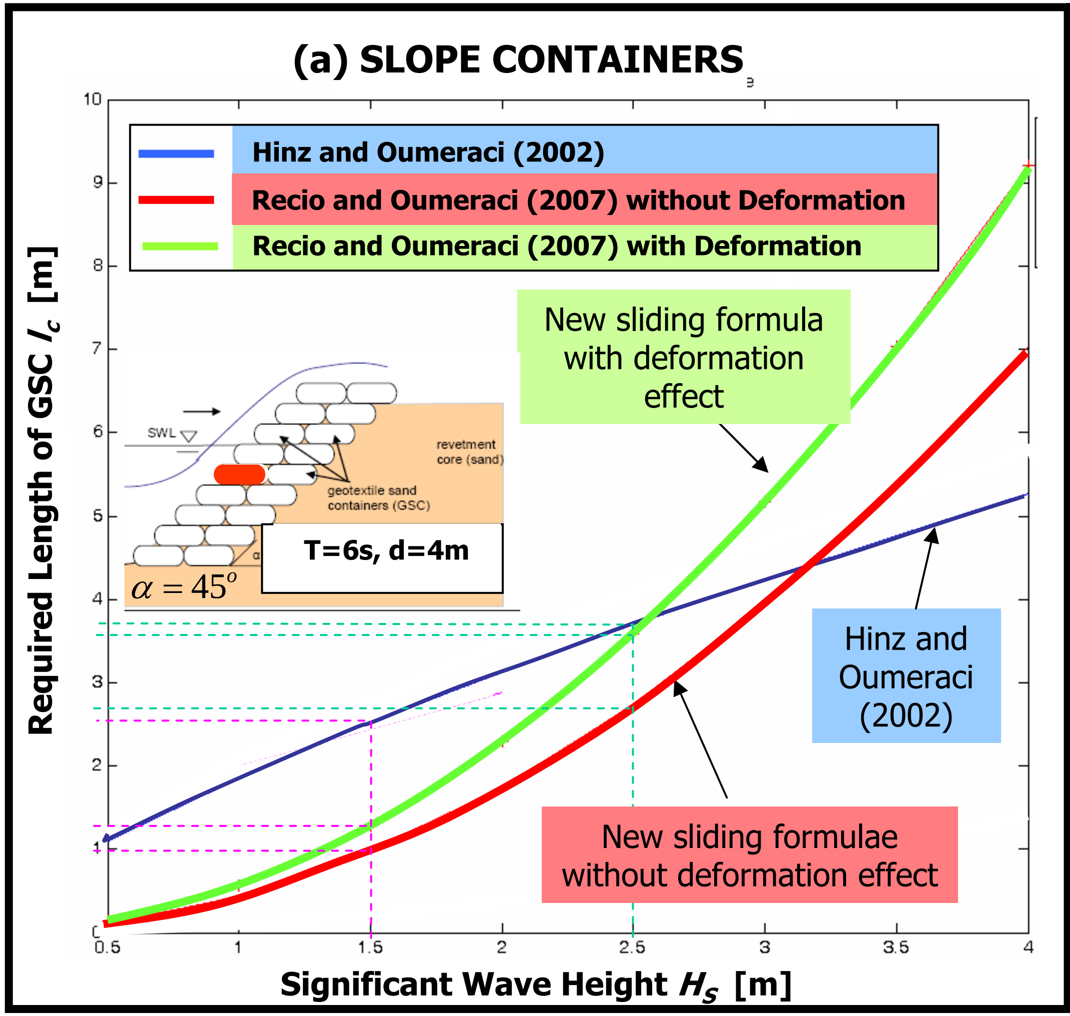
D is the length scale of GSC in the flow direction $D = l_c$ in meters

ν is the kinematic viscosity of water in m^2/s

KS_i is the deformation factor for sliding

KO_i is the deformation factor for overturning

5.4 Comparison Between Stability Formulae with and Without Deformation Effect for Slope GSCs and Crest GSCs



Hinz and Oumeraci (2002)

$$\frac{H_S}{\left(\frac{\rho_E}{\rho_W}-1\right)\cdot D} = \frac{2.75}{\sqrt{\xi_0}}$$

$$\xi_o = \frac{\tan\alpha}{\sqrt{H_s / L_o}} \quad D = l_c \sin\alpha \quad \rho_E = (1-n)\cdot\rho_s + \rho_w \cdot n$$

Sliding formulae without deformation effect

$$l_c \geq u^2 \frac{[0.5C_D + 2.5C_L\mu]}{\left[1.6\mu\Delta g - C_M \frac{\partial u}{\partial t}\right]}$$

$$C_D = 9 \quad C_M = 0.30 \quad C_L = 1.0$$

Sliding Formulae with Deformation Effect

$$l_c \geq u^2 \frac{[0.5KS_{CD}C_D + 2.5KS_{CL}C_L\mu]}{\left[\mu KS_R\Delta g - KS_{CM}C_M \frac{\partial u}{\partial t}\right]}$$

$$C_D = 9 \quad C_M = 0.30 \quad C_L = 1.0$$

$$KS_{CD} = 1.4 \quad KS_{CM} = 1.0 \quad KS_{CL} = 0.94 \quad KS_R = 1.6$$

For smaller waves ($H_S \leq 1.5$m):

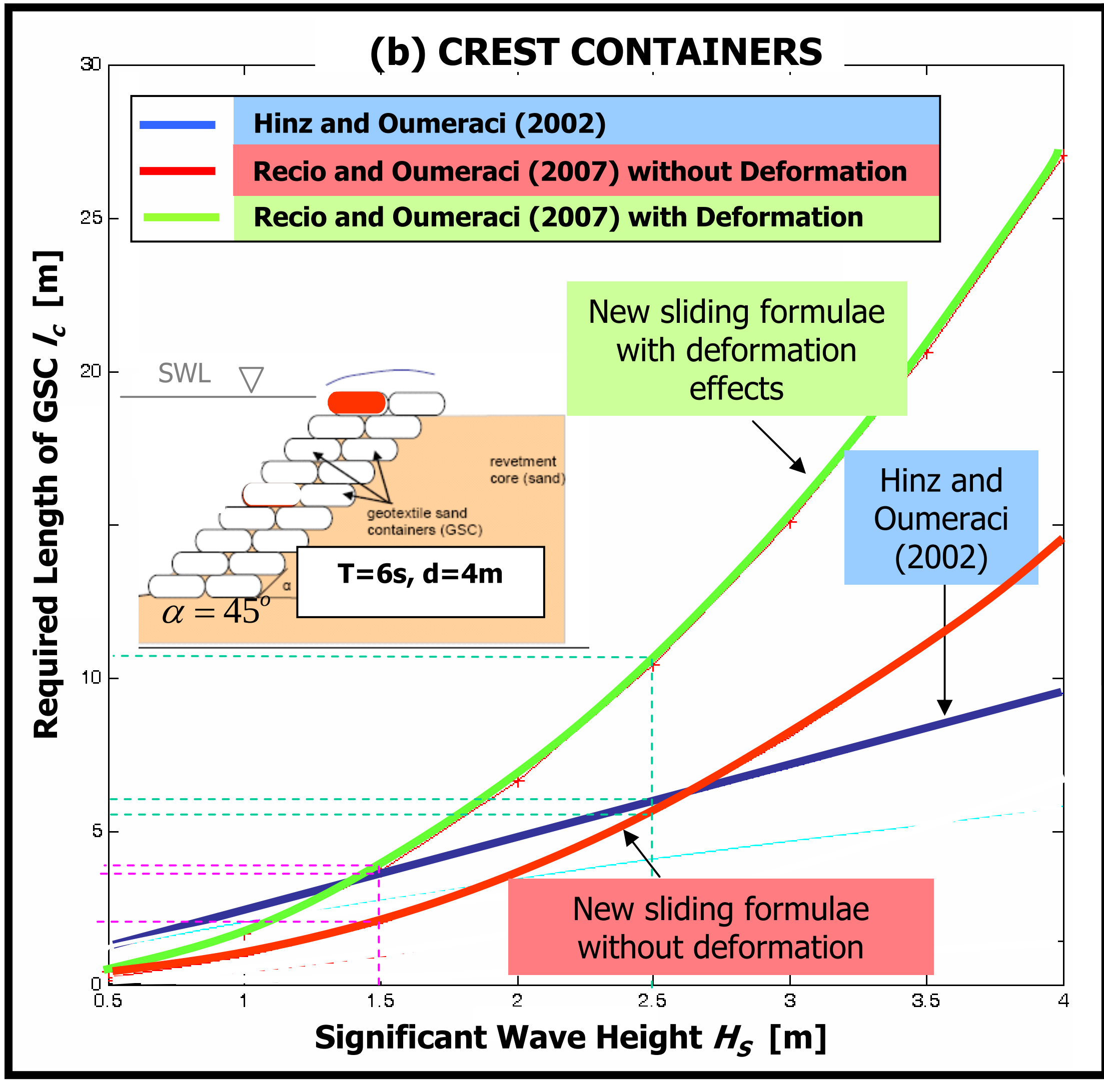
- simple stability formulae are largely conservative
- Deformation effects are small

For higher waves ($H_S \geq 2.5$m):

- simple stability formulae becomes unsafe
- Deformation effects becomes important for stability

→ Additional protection (e.g. Armouring) may be required

Stability Formulae for Crest Containers



Hinz and Oumeraci (2002)

$$\frac{H_S}{(\rho_E/\rho_W - 1)\cdot D} = 0.79 + 0.09\frac{R_C}{H}$$

$$\xi_o = \frac{\tan\alpha}{\sqrt{H_s/L_o}}$$

$$D = l_c \sin\alpha$$

$$\rho_E = (1-n)\cdot\rho_s + \rho_w\cdot n$$

Sliding formulae without deformation effect

$$l_c \geq u^2 \frac{[0.5C_D + 2.5C_L\mu]}{\left[1.6\mu\Delta g - C_M\frac{\partial u}{\partial t}\right]}$$

$C_D = 11 \quad C_M = 0.60 \quad C_L = 1.2$

Sliding Formulae with Deformation Effect

$$l_{c(sl)} \geq u^2 \frac{[0.5KS_{CD}C_D + 2.5KS_{CL}C_L\mu]}{\left[\mu KS_R\Delta g - KS_{CM}C_M\frac{\partial u}{\partial t}\right]}$$

$C_D = 11 \quad C_M = 0.60 \quad C_L = 1.2$

$KS_{CD} = 1.4 \quad KS_{CM} = 1.0 \quad KS_{CL} = 0.94 \quad KS_R = 0.70$

- Deformation effects more important than for slope containers
- Confirmation that required crest GSC is more than 3.5 times larger than slope GSC

6. Summary and Conclusions of the Short Course

- **After 50 years of successful experience of geotextiles in coastal engineering applications for shore protection are well established.**

- **Geotextile Sand Containers (GSCs) represent a soft and low cost alternative to conventional hard materials such as rock and concrete. Moreover, GSC-based solutions are versatile, environmentally friendly and easily reversible. As „soft construction units" of any size, GSCs can be used to build any type of shore protection structure, including scour protection and dune reinforcement.**

- **However, to make use of the full potential of GSCs, several problems still need to be solved, particularly those associated with:**

  - (i) their durability and life time prediction

  - (ii) their hydraulic stability under wave action.

- **Most failures experienced yet are rather due to bad design, bad choice of material and/or bad installation.**
- **Accelerated testing allows to study only a life time of <25 years and only in an incomplete manner.**
- **Field evidence is available up to 50 years, but useful information extracted from this is often very limited.**
- **Results of accelerated tests and field observations – even in combination – are still very limited to predict life time of more than 50 years.**

↓

What to do in the future and now?

Mid- and Long Term:

- **Improve understanding of degradation mechanisms, incl. physical, biological and chemical processes, both isolated and in combination.**
- **Develop consistent framework for life time prediction based on the above, incl. site monitoring, laboratory testing, theoretical/numerical simulations.**

Meanwhile ?

Meanwhile:

- **Apply engineering judgement based on present knowledge on degradation mechanisms rather than „extrapolations" to predict life time.**
- **Apply one or many of the following measures to ensure long-term performance.**
  - Additional stabilizers (e.g. against UV-radiation)
  - More robust geotexile (e.g. multi-layer)
  - Robust geotextile coating (e.g. against vandalism, abrasion, etc.)
  - Sand covering (to enhance protection against UV and vandalism)
  - Armour covering (e.g. against ice loads, very high waves, UV and vandalism)
  - Set-up of good maintenance plan (to correct any failure and act of vandalism).

Stability of Geotextile Sand Containers under Wave Action

- **Geotextile Sand Containers (GSCs) are subject to strong deformations, depending on the sand fill ratio and the intensity of wave action.**
- **The GSC-deformations are essentially induced by internal sand movement.**
- **Internal sand movement induced by wave action (under submerged conditions) can lead to a reduction of GSC-structure height by about 10%.**
- **GSC-deformations do affect the stability due to**
  - **reduction of contact area between GSC by uplifting**
  - **increase of exposed GSC-areas, leading to increased drag and uplift forces.**
- **For smaller waves ($H_s \leq 1.5$ m): available simple HUDSON-type stability formulae are conservative and deformation effects are less critical.**
- **For higher waves ($H_s \geq 2.5$ m): available simple formulae are unsafe and deformation effects become very important. Additional protection (e.g. armouring) might be required to ensure long-term stability.**

Further Important Effects on Hydraulic Stability

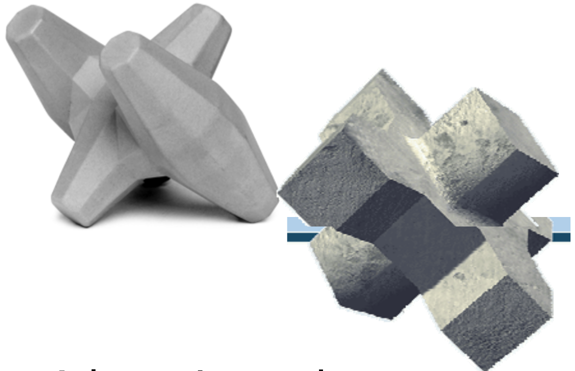
- **Friction between GSCs influences stability more than commonly assumed in the design practice.**
- **Hydraulic permeability (*k)* of GSC-structures is essentially determined by the gaps between GSCs, and thus by the mode of placement. For randomly and longitudinally placed GSCs, *k* is in the order of 2.0-2.5 cm/s (at least one order of magnitude less than gravel).**
- **Permeability of GSC-structures slightly affects stability, but correlation is still not clear.**
- **Effect of breaking wave impact on sliding and overturning stability of slope containers is less than expected.**

Rubble Mound Structure and GSC Structures: The Way Forward?

Development Stages of Rubble Mound Strucutres

Purely empirical

Understanding of Processes and Stability Formulae



Adaptation to large waves, optimizations, etc.

Development Stages of Coastal Structures made with GSC

Purely empirical

Understanding of Processes and Stability Formulae

<u>Ongoing Research:</u>

- **Further improvement of process-understanding**
- **Durability and life time prediction**
- **Specification of fill ratio and friction for life cycle**

Rock and concrete are not always the best solution!