REVISED RECESSION OF RESHAPING BERM BREAKWATERS

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In this paper data has been collected on berm breakwater stability from several laboratories. The total database contains more than 1500 model test data on berm recession. The data has been compared to five existing recession formulae and most of the existing recession formulae provide good estimates within the validation area of the formula. The Lykke Andersen formula has the largest application area and provides reliable results in most cases. A slightly modified version of that formula is suggested and it is shown that the new formula has a very large application area and provides less uncertainty for partly and fully reshaping structures than other methods to assess the stability.

Keywords: rubble-mound breakwater; berm breakwater; recession; stability

INTRODUCTION

Berm breakwaters can be classified based on their structural behavior into hardly, partly and fully reshaping. Sigurdarson and Van der Meer (2012) gave indicative values for the three types in terms of stability number, $H_s/\Delta D_{n50}$, the damage, S_d, and the recession, Rec/D_{n50}.

For the hardly reshaping berm breakwaters Lykke Andersen et al. (2012) and Burcharth (2013) suggested to use the eroded area as damage parameter instead of the berm recession. Lykke Andersen et al. (2012) found for such structures excellent agreement with the formulae for straight slopes (Van der Meer (1988)) if the plunging formula was always used. Burcharth (2013) used a similar method and found good agreement with the observed prototype damage in Sirevåg breakwater.

However, for reshaping berm breakwaters the berm recession is the most important parameter for the stability. The present paper will give a detailed review of existing recession formulae and their range of applicability.

Lykke Andersen and Burcharth (2010) evaluated existing recession formulae as well as proposing a new one based on 13 model test datasets with in total app. 1000 model tests. The datasets cover both mass armoured and Icelandic type berm breakwaters.

Since then several new model test studies have been carried out resulting in much more data and new recession formulae, cf. Moghim et al. (2011) and Shekari and Shafieefar (2012). These two formulae use the stability number $H_0\sqrt{T_0}$ which was found by Moghim et al. (2011) to properly include the effect of the wave period. Moghim and Alizaden (2014) presented a new recession formula based on the maximum momentum flux parameter as an alternative to $H_0\sqrt{T_0}$.

All the new recession formulae have a much simpler form than the Lykke Andersen formula but exclude the influence of important parameters like the front slope. Moreover, the new formulae are in general validated on much fewer data sets and with very limited variation in the water depth.

Tørum et al. (2012) investigated the applicability of several recession formulae and concluded that all formulae gave reasonable results in shallow water. However, for deep water conditions they found the Lykke Andersen formula to be the best one. The reason for this is expected to be that Lykke Andersen and Burcharth (2010) included the influence of the water depth, front slope and berm elevation based on some characteristics of the reshaped profile instead of pure empirical fitting as used for the other formulae.

In the present paper is established a recession database and the different recession formulae are evaluated against the database. The database includes all data sets used in Lykke Andersen and Burcharth (2010) as well as several new data sets. The areas of application of the different formulae are studied and recommendations on when to use the formulae for static stability and recession are given. The inclusion of the $H_0\sqrt{T_0}$ stability parameter in the Lykke Andersen recession formula is investigated as well.

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RECESSION DATABASE

The established recession database is based on berm breakwater model test data from 20 datasets (see Table 1) giving in total 1576 model test data. The database contains for all tests the following parameters:

1. Test number
2. Test number of preceding test (-1 if structure rebuilt prior to this test)
3. Spectral wave height (H_{m0})
4. Spectral mean period ($T_{m0,1}$)
5. Number of waves in test (N)
6. Wave obliquity (β)
7. Median stone diameter, i.e. the diameter exceeded by 50% of the units (D_{n50})
8. Stone gradation factor (f_g)
9. Reduced relative density ($\Delta = \rho_s / \rho_w - 1$)
10. Water depth at toe of structure (h)
11. Water depth above toe (h_t)
12. Slope angle below berm ($\cot(\alpha_d)$)
13. Slope angle above berm ($\cot(\alpha_u)$)
14. Initial berm width (B)
15. Water depth above berm (h_b)
16. Crest freeboard (R_c)
17. Berm recession (Rec)

Additionally the database contains for some tests other deformation parameters like eroded area (A_e), step height (h_s), depth of intersection (h_f) and also other wave parameters (T_p, $H_{2\%}$, skewness, etc.). The plan is to continuously develop the database with new data and also with more parameters for existing data.

The database includes at present stage 106 model test data for hardly reshaping ($Rec/D_{n50} \leq 2$), 185 model test data for partly reshaping ($2 < Rec/D_{n50} \leq 5$) and 1165 data for fully reshaping structures ($Rec/D_{n50} > 5$). Thus the main part of the database is at present for fully reshaping structures, but a very significant amount of data is still included for hardly and partly reshaping berm breakwaters. The data in the database comes from the following laboratories:

- Aalborg University, Denmark (37% of database)
- Tarbiat Modares University, Iran (26% of database)
- DHI, Denmark (16% of database)
- SCWMRI, Iran (9% of database)
- Queens University, Canada (7% of database)
- Deltares (3% of database)
- SINTEF, Norway (2 % of database)

Thus a few laboratories represent the main part of the data in the database. The database covers berm breakwaters in both deep and shallow water and both long and steep waves. Table 1 provides an overview of the individual datasets included in the database. Note that for the datasets in Table 1 marked with an asterisk the waves are not measured at the toe of the structure, but is calculated with SWAN using data at deeper water. These datasets thus include more uncertainty on wave conditions than the others. The following definitions of stability indices and wave steepness are used throughout the paper:

$$H_0 = \frac{H_{m0}}{\Delta D_{n50}}$$

$$T_0 = T_{m0,1}\sqrt{\frac{g}{D_{n50}}}$$

$$s_{0m} = \frac{H_{m0}}{\frac{g}{2\pi}T_{m0,1}^2}$$

Table 1. Overview of recession database. Type indicates number of tests in respectively hardly, partly and fully reshaping based on Rec/D_{n50} limits given above. Datasets marked with * means wave parameters at the toe are calculated from waves at deeper water.

Reference	No. tests	Type	Cot(α)	H_0	T_0	s_{0m} [%]	H_{m0}/h	h_t/D_{n50}	h_{br}/H_{m0}	B/H_{m0}	Rec/D_{n50}
Instanes (1987)*	7	0 / 3 / 4	1.5	2.9-3.5	21-23	7.3	0.54	9.7-11.6	0.22	2.8	1-15
Tørum et al. (1988)*	13	1 / 0 / 12	1.5	1.6-4.4	27-32	2.5-6.6	0.17-0.46	17.2	0.4-1.2	1.9-5.3	1-25
Van der Meer (1988)	51	4 / 1 / 46	1.5	1.4-6.0	19-49	1.9-5.7	0.07-0.31	31.1	-1.2	2.4-10.4	0-33
Burcharth and Frigaard (1990)	5	0 / 0 / 5	1.5	3.6-7.2	32-53	2.0-3.8	0.20-0.40	29.6	1.3-2.5	0	1-28
Andersen and Poulsen (1991)	178	3 / 12 / 163	1.1	0.7-5.1	16-38	1.7-4.7	0.05-0.37	19.8-26.5	0.3-2.7	2.3-12.1	1-33
Hall (1991)	108	0 / 9 / 99	1.25	1.7-4.9	17-14	2.7-9.1	0.13-0.39	21.1	0.2-0.5	1.8-8.9	1-28
Lissev (1993)	12	5 / 0 / 7	1.25	1.2-4.8	18-34	3.9-4.5	0.09-0.35	23	0.3-1.2	2.4-9.6	0-17
Aalborg University (1995)	4	0 / 0 / 4	1.0	3.1-4.4	23-27	5.5-7.0	0.25-0.35	13.6-15.5	1.2-1.6	0	1-23
DHI (1995)	30	0 / 8 / 22	1.1	1.5-4.2	20-35	2.5-4.8	0.11-0.29	21.7	0.6-1.7	4.0-11.0	1-26
DHI (1996)*	50	9 / 20 / 21	1.1	1.4-3.4	20-28	3.1-6.3	0.30-0.51	6.4-11.4	0.4-1.3	2.8-4.9	0-15
Juul Larsen (2002)*	20	0 / 1 / 19	2.0	3.4-5.4	25-33	3.6-6.9	0.44-0.55	12.5-17.9	-0.2-0.9	0-3.6	1-25
Porarinson (2004)*	7	7 / 0 / 0	1.05	0.4-1.7	9-24	3.3-6.9	0.12-0.56	4.0	0.7-3.0	2.2-10.1	0-1
Lykke Andersen (2006)	451	22 / 48 / 381	1.25	1.0-4.9	17-40	1.3-6.2	0.15-0.56	8.8-22.2	-1.8 -3.5	0 - 8.7	0 – 30
Lykke Andersen et al. (2008)	12	8 / 3 / 1	1.5	1.1-2.9	16-29	27-5.9	0.20-0.55	10	0.5-1.2	1.1-3.1	0-5
AAU projects (2009)	8	2 / 5 / 1	1.1 , 1.3	1.6-2.6	18-25	3.8-8.1	0.19-0.29	9.6-15	0.5-1.2	2.1-4.8	0-6
Motalebi (2010)	120	18 / 35 / 67	1.25	1.7-4.2	22-30	2.4-4.3	0.20-0.49	8.0-16.5	-0.7-1.4	2.1-5.4	0-17
Moghim et al. (2011)	144	1 / 2 / 141	1.25	1.6-4.2	20-37	1.3-7.2	0.18-0.54	9.5-16.5	0.1-1.2	2.3-9.3	1-22
Shekari and Shafieefar (2013)	287	8 / 57 / 222	1.25	1.6-3.9	17-31	1.7-10.4	0.19-0.50	8-16.5	0.1-1.1	3.1-8.9	1-22
Bătăcui & Ciocan (2013)	44	20 / 8 / 16	1.25 , 1.5	0.9-2.9	16-37	1.3-5.2	0.15-0.48	10.7	0.1-0.8	1.2-3.8	0-7
Thomsen et al. (2014)	25	16 / 8 / 1	1.5	1.4-2.2	34-47	0.9-1.4	0.16-0.42	6.1-17.6	0-1.9	1.3-3.8	0-6

EXISITNG RECESSION FORMULAE

Lykke Andersen and Burcharth (2010) provided a comprehensive review of the existing recession formulae. Based on a large amount of model test data was provided a recession formula much more general applicable than the other formulae. Thus the formulae of Hall and Kao (1991), Tørum (1998), Tørum and Krogh (2000) will not be considered again in this paper. However, more recent formulae have been proposed by Moghim et al. (2011), Shekari and Shafieefar (2013), Sigurdarson and Van der Meer (2013) and Moghim and Alizaden (2014).

Lykke Andersen and Burcharth (2010)

This formula was established based on some considerations of the shape of the reshaped profile with changing water depth, berm elevation and front slope. Volume conservation gave a formula of the following form:

$$\frac{Rec}{D_{n50}} = f_{hb}\left[\frac{2.2 \cdot h_t - 1.2 \cdot h_s}{h_t - h_b} \cdot \frac{Rec_1}{D_{n,50}} + \frac{[\cot(\alpha_d) - 1.05]}{2D_{n50}} \cdot [h_b - h_t]\right] \quad (1)$$

In Eq. 1 an additional factor f_{hb} was included to account for berms below SWL (not a typical berm breakwater). Rec_1 is the recession in situation 1 where the front slope equals the natural angle of repose, berm elevation at SWL and water depth equals the step height (see Fig. 1). *Rec* is the recession in situation 2, i.e. the case in which the recession needs to be calculated. For more information refer to Lykke Andersen and Burcharth (2010).

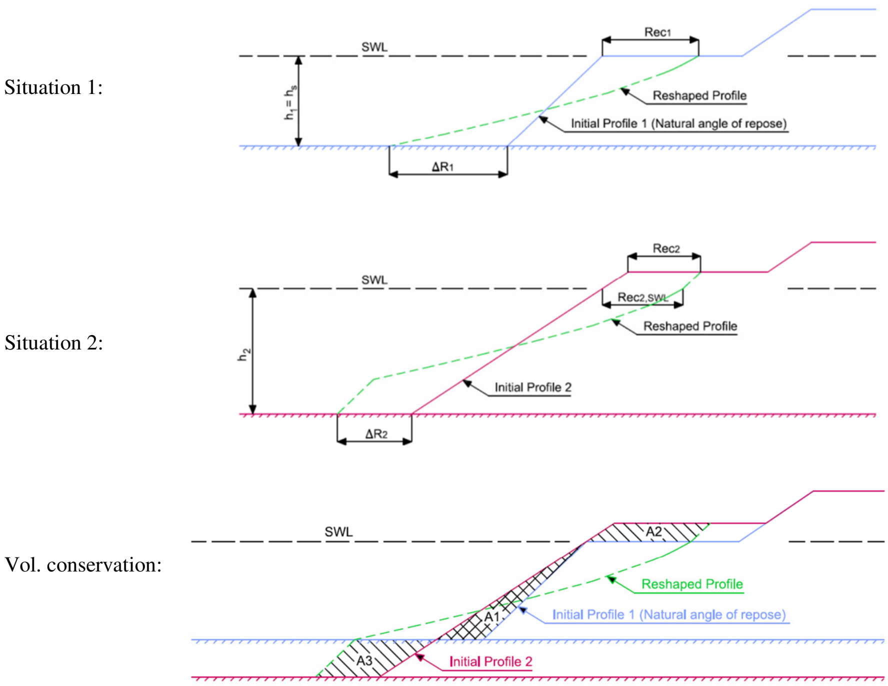

Figure 1. Definition of situation 1 and 2 and areas A1, A2 and A3.

The recession in situation 1 was taken as the product of the five functions f_{H0}, f_β, f_N, $f_{grading}$ and $f_{skewness}$ calibrated to the test data (see Lykke Andersen and Burcharth (2010)).

$$\frac{Rec_1}{D_{n50}} = f_{H0} \cdot f_\beta \cdot f_N \cdot f_{grading} \cdot f_{skewness} \quad (2)$$

f_{H0} account for the influence of the stability index H_0, T_0 and wave steepness s_{0m}. f_β account for oblique waves, f_N account for the number of waves, $f_{grading}$ for the stone gradation factor and $f_{skewness}$ for breaking non-linear waves observed to give more reshaping than non-breaking waves.

Moghim et al. (2011)

Moghim found that the governing stability number was $H_0\sqrt{T_0}$. Besides this his formula includes the influence of number of waves, berm elevation and water depth:

$$\frac{Rec}{D_{n50}} = f_{H0} \cdot f_N \cdot f_{hb} \cdot f_h \quad (3)$$

In case the data are outside the validity range of h_b ($-1.24 \leq h_b/H_{m0} \leq -0.12$) the limit of the validity range is applied. This is because the formula has singular points at $h_b \geq 0$, but data exist in the database for very low berms ($h_b \geq 0$).

Shekari and Shafieefar (2013)

Compared to the Moghim et al. (2011) formula Shekari and Shafieefar (2013) excluded the influence of the water depth and included instead a small influence of the berm width. Their formula reads:

$$\frac{Rec}{D_{n50}} = f_{H0} \cdot f_N \cdot f_{hb} \cdot f_B \tag{4}$$

For data outside the validity ranges of B ($14 \leq B/D_{n50} \leq 29.4$) and h_b ($-1.57 \leq h_b/D_{n50} \leq -0.22$) has in this study the limit of the validity range been applied. This is because the formula has singular points at $h_b \geq 0$ and $B = 0$ which have been tested in some of the cases in the database. The f_{H0} formula has also limited application area, but is in this case applied also outside of that area.

Sigurdarson and Van der Meer (2013)

This formula includes only the influence of the stability number H_0. The formula reads:

$$\frac{Rec}{D_{n50}} = f_{H0} \tag{5}$$

The validity range of the formula is not specified, but is assumed to be $H_0 \leq 3.5$, $h_b<0$ and $N \geq 500$.

Moghim and Alizadeh (2014)

Moghim and Alizadeh used the wave momentum flux parameter (N_m) instead of $H_0\sqrt{T_0}$. N_m is given by the maximum momentum flux M_F as:

$$N_m = \sqrt{\frac{M_F}{\Delta \gamma_w D_{n50}^2}}$$

$$M_F = \gamma_w h^2 A_0 \left(\frac{h}{gT_m^2}\right)^{-A_1} \qquad A_0 = 0.639\left(\frac{H_{m0}}{h}\right)^{2.026} \qquad A_1 = 0.180\left(\frac{H_{m0}}{h}\right)^{-0.391}$$

Their recession formula is similar to that by Moghim et al. (2011) formula except that the product of f_{H0} and f_h is replaced by f_{Nm}:

$$\frac{Rec}{D_{n50}} = f_{Nm} \cdot f_N \cdot f_{hb} \tag{6}$$

$$f_{Nm} = 2.85 N_m - 7.36$$

The water depth is considered to impact only the recession through the momentum flux. The effect that an increase in depth also increases the deposited volume is neglected.

Evaluation of Existing Formulae

In Figs. 2-6 the above formulae are tested on the basis of the database. When a test is outside the validated range for any of the parameters the test is plotted with a red marker.

Some data sets include very large recessions far from typical design values. Thus in the evaluation focus is on the area $0 \leq Rec/D_{n50} \leq 15$. In the figures an upper limit at 25 is used to make sure most of the data with measured or predicted recession in the relevant area is included - also for relative large deviations between formulae and data. The small amount of data points having a Reynolds number, $Re<10^4$ has been disregarded due to possible scale effects.

In all figures has been included a band given by:

$$\begin{aligned} \frac{Rec_{5\%}}{D_{n,50}} &= 0.76\frac{Rec_{50\%}}{D_{n,50}} - 2.50 \\ \frac{Rec_{95\%}}{D_{n,50}} &= 1.31\frac{Rec_{50\%}}{D_{n,50}} + 2.50 \end{aligned} \tag{7}$$

This band contains most of the data within the validated ranges for the best formulae (see Figs. 2-6). The Lissev (1993) dataset contains less damage than predicted by all formulae as most points are far outside the band. The reason for this deviation was not identified.

For the Motalebi (2010) dataset the formulae is in most cases giving a safe bias. These tests are performed with a lower stone density (Δ = 1.35) than used in the other tests, but is otherwise quite similar to for example the Shekari and Shafieefar (2013) dataset which on the other hand provides more damage than predicted by the formulae.

Hall (1991) studied the influence of the stone gradation. For typical gradation factors ($f_g \leq 2.5$) a wider gradation leads to more recession, but the tendency is different for the unusual wide gradation (f_g = 5.4) also tested by Hall (1991) given with square symbols in Figs. 2-7. The increased stability for such wide gradation was on the safe side not included in the fitting of $f_{grading}$ in the Lykke Andersen and Burcharth (2010) formula.

The dataset of Juul Larsen (2002) relates to a fully reshaping breakwater with initial front slope 1:2. Although not a realistic breakwater, the data was included for verification of the possible validity of the Lykke Andersen and Burcharth (2010) formula for such a flat slope when the structure is fully reshaping.

The Moghim et al. (2011) and Shekari and Shafieefar (2013) formulae both provide reliable predictions within their validation area, but the specified validation area is so narrow that almost only the data used to fit the formulae is inside. For data outside the validation area the scatter is significantly larger.

The Sigurdarson and Van der Meer (2013) formula provides a very unsafe prediction for the Moghim et al. (2011) and Shekari and Shafieefar (2013) datasets for the entire range from hardly to fully reshaping structures. This is observed also for data points within the defined application area. This is expected because the formula disregards the influence of some important parameters like water depth, wave period and front slope. For the other datasets the predictions are quite good when considering the very simple formula.

The Lykke Andersen and Burcharth (2010) formula provides by far the widest application area and gives reliable estimates in almost every case. However, for hardly and partly reshaping structures it predicts too much recession for sea states with high wave skewness (Lykke Andersen et al. (2008), Batacui and Ciocan (2013), Thomsen et al. (2014) datasets). The wave skewness was included in the formula because it improved the recession prediction for the fully reshaping structures, but for the more stable structures it leads to predictions which are too conservative.

IMPROVED LYKKE ANDERSEN FORMULA

The extended database revealed a problem with the formula of Lykke Andersen and Burcharth (2010) for high wave skewness. Therefore, the influence of the wave skewness is neglected in the present proposed formula. As in the original formula the recession is based on the recession in the simplified situation 1, but with new functions for f_{H0} based on the stability number $H_0\sqrt{T_0}$ as suggested by Moghim et al. (2011). This leads to a simpler formula with similar performance.

$$\frac{Rec_1}{D_{n50}} = f_{H0} \cdot f_\beta \cdot f_N \cdot f_{grading}$$

with the four functions given by:

$$f_{H0} \overset{\min}{=} \begin{cases} -4.7 \cdot 10^{-5}\left(H_0\sqrt{T_0}\right)^4 + 1.6 \cdot 10^{-3}\left(H_0\sqrt{T_0}\right)^3 + 2.2 \cdot 10^{-2}\left(H_0\sqrt{T_0}\right)^2 + 3.8 \cdot 10^{-2} H_0\sqrt{T_0} \\ 0.429 \cdot H_0\sqrt{T_0} + 12.0 \end{cases}$$

$$f_N = \left(\frac{N}{3000}\right)^{\varphi} \quad \varphi = \begin{cases} 0.30 & for \quad H_0\sqrt{T_0} \leq 24 \\ 0.64 - 0.0143 H_0\sqrt{T_0} & for \quad 24 > H_0\sqrt{T_0} > 40 \\ 0.07 & for \quad H_0\sqrt{T_0} \geq 40 \end{cases}$$

$$f_\beta = \cos(\beta)$$

$$f_{grading} = \begin{cases} 1 & for\ f_g \leq 1.5 \\ 0.43 \cdot f_g + 0.355 & for\ 1.5 < f_g < 2.5 \\ 1.43 & for\ f_g \geq 2.5 \end{cases}$$

Note that f_β and $f_{grading}$ are unchanged compared to the formula of Lykke Andersen and Burcharth (2010). The final change compared to the original formula is to correct a wrongly calculated deposited volume at the toe in situation 2 for cases in which the reshaping profile does not extend to the toe but intersects with the original profile (A3 area as defined in Fig. 1 is incorrect in that case). Even though it leads to a more complex formula, and only plays a role for rare cases with very deep water or flat slopes, it has been corrected by putting an upper limit to h_t in Eq. 1 i.e.:

$$h_t^* = \min\left(h_t \ ; \ \sqrt{\frac{2Rec_1}{\cot(\alpha_d) - 1.05} \cdot \left[1.2h_s \text{ - } 2.2h_{b*}\right] + h_{b*}^2} \right)$$

$$h_{b*} = \min(h_b \ ; 0.0)$$

f_{hb} and h_s is unchanged compared to the formula of Lykke Andersen and Burcharth (2010), i.e.:

$$h_s = 0.65 \cdot H_{m0} \cdot s_{0m}^{-0.3} \cdot f_N \cdot f_\beta$$

$$f_{hb} = \begin{cases} 1 & for \ \dfrac{h_b}{H_{m0}} \leq 0.1 \\ 1.18 \cdot \exp\left(-1.64 \cdot \dfrac{h_b}{H_{m0}} \right) & for \ \dfrac{h_b}{H_{m0}} > 0.1 \end{cases}$$

The final formula to calculate the recession is given as a function of above parameters as:

$$\frac{Rec}{D_{n50}} = f_{hb} \left[\frac{2.2 \cdot h_t^* - 1.2 \cdot h_s}{h_t^* - h_b} \cdot \frac{Rec_1}{D_{n,50}} + \frac{\left[\cot(\alpha_d) - 1.05\right]}{2D_{n50}} \cdot \left[h_b - h_t^*\right] \right] \quad (8)$$

In Fig. 7 the new formula is evaluated against the database. Table 2 presents the average error calculated from Eq. 9 for the different formulae.

$$E = \frac{1}{N} \sum_{i=1}^{N} \left| \frac{Rec_{calc} - Rec_{meas}}{D_{n50}} \right| \quad (9)$$

Table 2. Average error (*E*) as defined in Eq. 9 for data with measured *Rec*/*D*$_{n50}$<15.

	Data inside validation area						All data					
Reference	Eq. 2	Eq. 3	Eq. 4	Eq. 5	Eq. 6	Eq. 8	Eq. 2	Eq. 3	Eq. 4	Eq. 5	Eq. 6	Eq. 8
Instanes (1987)*	1.9	1.6	-	4.1	-	2.6	1.9	1.6	2.9	4.1	3.6	2.6
Tørum et al. (1988)*	3.9	-	-	4.0	-	2.1	3.9	2.3	2.5	9.2	3.2	2.1
Van der Meer (1988)	3.3	-	-	1.2	-	3.6	3.3	15.2	6.3	7.0	10.3	3.6
Burcharth & Frigaard (1990)	1.2	-	-	-	-	1.0	1.2	13.0	6.6	6.9	8.8	1.0
Andersen & Poulsen (1991)	2.6	-	-	2.9	-	1.6	2.6	2.3	1.5	3.1	1.3	1.6
Hall (1991)	3.1	-	-	2.9	9.7	3.0	3.1	5.3	3.2	3.2	4.5	3.0
Lissev (1993)	7.9	-	-	4.0	8.8	7.6	7.9	10.0	7.7	13.8	8.9	7.6
Aalborg University (1995)	1.4	-	-	3.2	-	1.8	1.4	0.9	1.2	4.1	1.2	1.8
DHI (1995)	1.6	-	-	1.9	-	1.2	1.6	3.5	1.4	1.9	2.4	1.2
DHI (1996)*	1.7	1.6	3.4	1.6	-	1.5	1.7	1.6	2.3	1.6	2.5	1.5
Juul Larsen (2002)*	3.3	10.6	-	0.4	-	2.9	3.3	12.2	13.6	19.3	18.1	2.9
Porarinson (2004)*	0.1	-	-	0.3	-	0.2	0.1	3.8	3.3	0.3	0.2	0.2
Lykke Andersen (2006)	1.1	1.5	2.5	2.4	3.0	1.3	1.1	4.0	2.7	2.5	3.9	1.3
Lykke Andersen et al. (2008)	0.9	1.4	-	0.6	-	0.8	0.9	1.6	2.0	0.6	2.0	0.8
AAU projects (2009)	1.2	2.8	2.6	0.7	-	1.0	1.2	1.6	1.6	0.7	2.3	1.0
Motalebi (2010)	4.9	-	6.8	1.9	-	3.1	4.9	4.2	5.3	3.1	4.5	3.1
Moghim et al. (2011)	1.6	0.9	1.6	4.6	1.4	2.6	1.6	0.9	1.1	4.9	1.4	2.6
Shekari & Shafieefar (2013)	2.4	1.4	1.2	4.2	1.1	1.0	2.4	1.4	1.3	4.2	1.0	1.0
Bătăcui & Ciocan (2013)	2.1	2.7	-	1.2	3.2	0.6	2.1	2.6	3.5	1.3	2.9	0.6
Thomsen et al. (2014)	1.3	-	-	1.3	-	1.2	1.3	4.0	3.8	1.3	3.8	1.2
All data	**2.4**	**1.5**	**1.9**	**2.9**	**2.0**	**2.2**	**2.4**	**3.2**	**2.7**	**3.6**	**3.1**	**2.2**

The new formula is more universal than the other formulae although the improvement over the original Lykke Andersen and Burcharth (2010) formula is in most cases very limited. The percentage of data inside the confidence band defined by Eq. 7 is 92.3% for the new formula when considering all data with $Rec \leq 15D_{n50}$ and $Re > 10^4$. The data outside the confidence band stems mainly from the Shekari and Schafieefar (2013) dataset and a few other datasets. For most other datasets the percentage of data inside the confidence band is much higher (e.g. 99.0% for Lykke Andersen (2006) dataset).

RECOMMENDED STABILITY ASSESSMENT TOOLS FOR BERM BREAKWATERS

The uncertainty of the new recession formula can be compared to the static stability formulae for straight slopes. The Van der Meer (1988) static stability formula has an upper 95% confidence level given by:

$$\begin{aligned} S_{D,95\%} &= 1.49 S_{D,50\%} \quad \text{for plunging waves} \\ S_{D,95\%} &= 1.63 S_{D,50\%} \quad \text{for surging waves} \end{aligned} \tag{10}$$

Compared to Eq. 7 it can thus be seen that the recession formula provide similar uncertainty as the static stability formulae when $Rec \approx 10\ D_{n50}$. However, the static stability formulae are for straight slopes in non-breaking conditions. Scatter might be higher for berm breakwaters and also in shallow water. Van Gent (2004) showed that by including data from shallow water the scatter was much higher than in the Van der Meer (1988) data. He suggested an updated Van der Meer formula including both deep and shallow water data with the 95% confidence level given by:

$$\begin{aligned} S_{D,95\%} &= 2.1 S_{D,50\%} + 2 \quad \text{for plunging waves} \\ S_{D,95\%} &= 2.9 S_{D,50\%} + 2 \quad \text{for surging waves} \end{aligned} \tag{11}$$

It can thus be seen that inclusion of shallow water data increases the uncertainty significantly. To compare the uncertainty of Eq. 7 and Eq. 11 a relation between Rec and S_D is needed as both formulae include a constant error term in addition to the proportional term. For typical conditions is found that the uncertainty of Van Gent (2004) formula and the recession formula is identical when $Rec \approx 1$ - 3 D_{n50}. This means that the recession formula lead to the smallest scatter for partly and fully reshaping structures.

CONCLUSIONS

A berm breakwater recession database with more than 1500 model test data has been established with the purpose to compare the many recession formulae proposed lately. Most of the recent recession formulae perform very well inside the validation area, but most formulae have a very narrow validation area. The Lykke Andersen and Burcharth (2010) formula has the widest application area and provides usually reliable results. The formula has been updated in the present paper as the influence of the wave skewness was observed to be much less than predicted for more stable structures. Moreover, the new formula solves a problem with application to very deep water situations for which unsafe results were obtained by the original formula. Finally the formula was refitted to include the $H_0\sqrt{T_0}$ stability index. The performance of the new formula is slightly better than the existing formulae.

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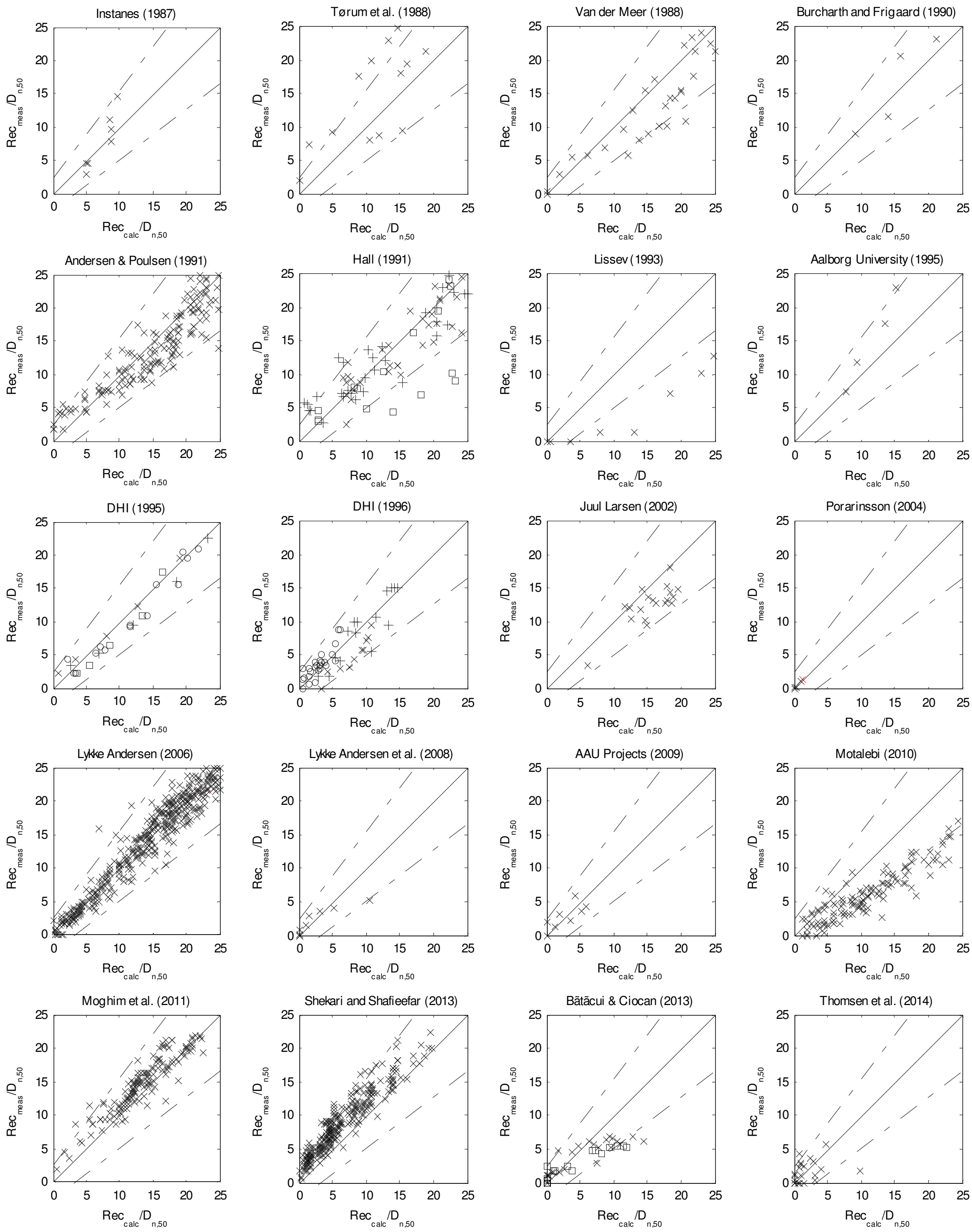

Figure 2. Evaluation of Lykke Andersen and Burcharth (2010) formula (Eq. 2) against the database. Red points are data outside validation area (h_s>h).

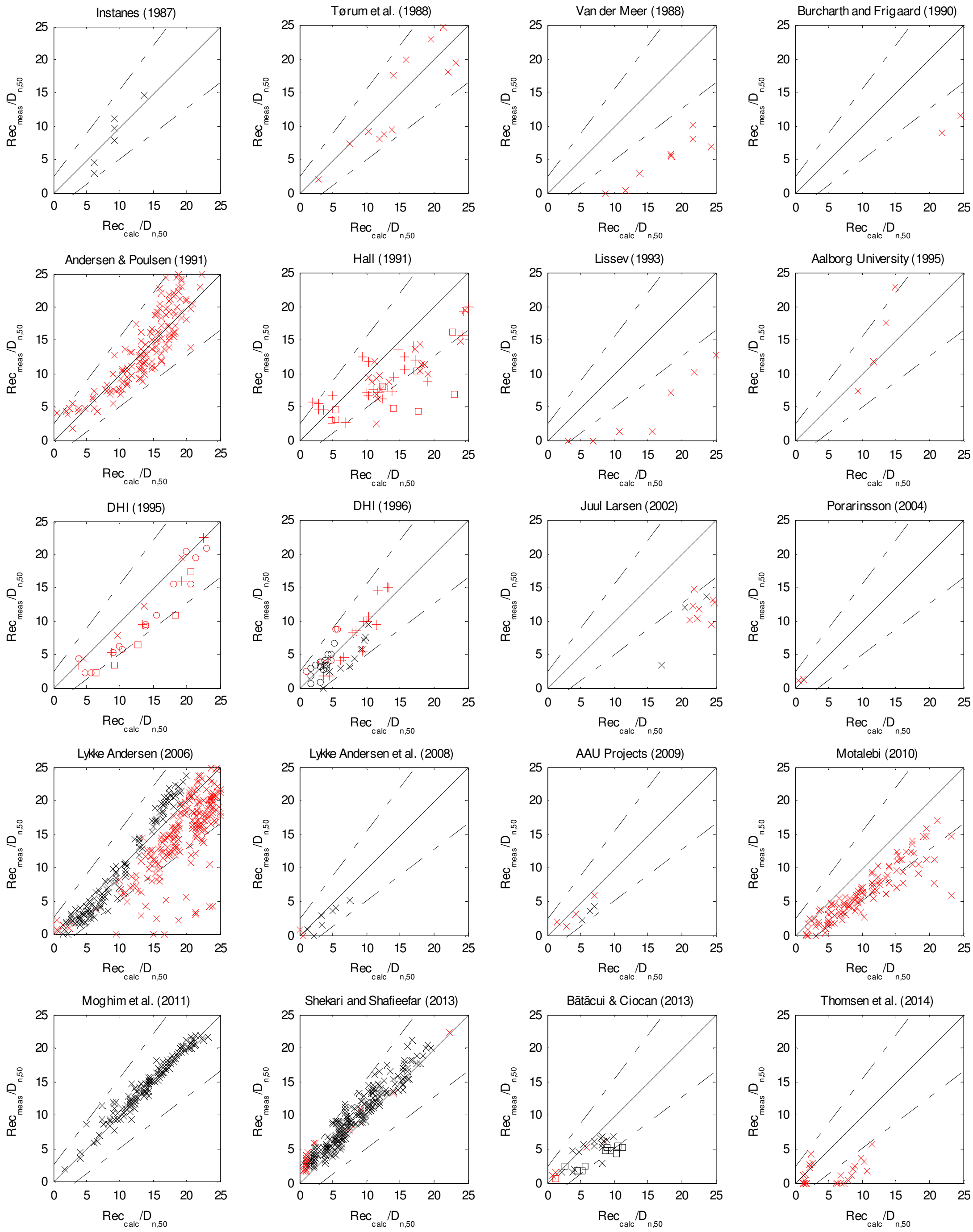

Figure 3. Evaluation of Moghim et al. (2011) formula (Eq. 3) against the database. Red points are data outside the validation area.

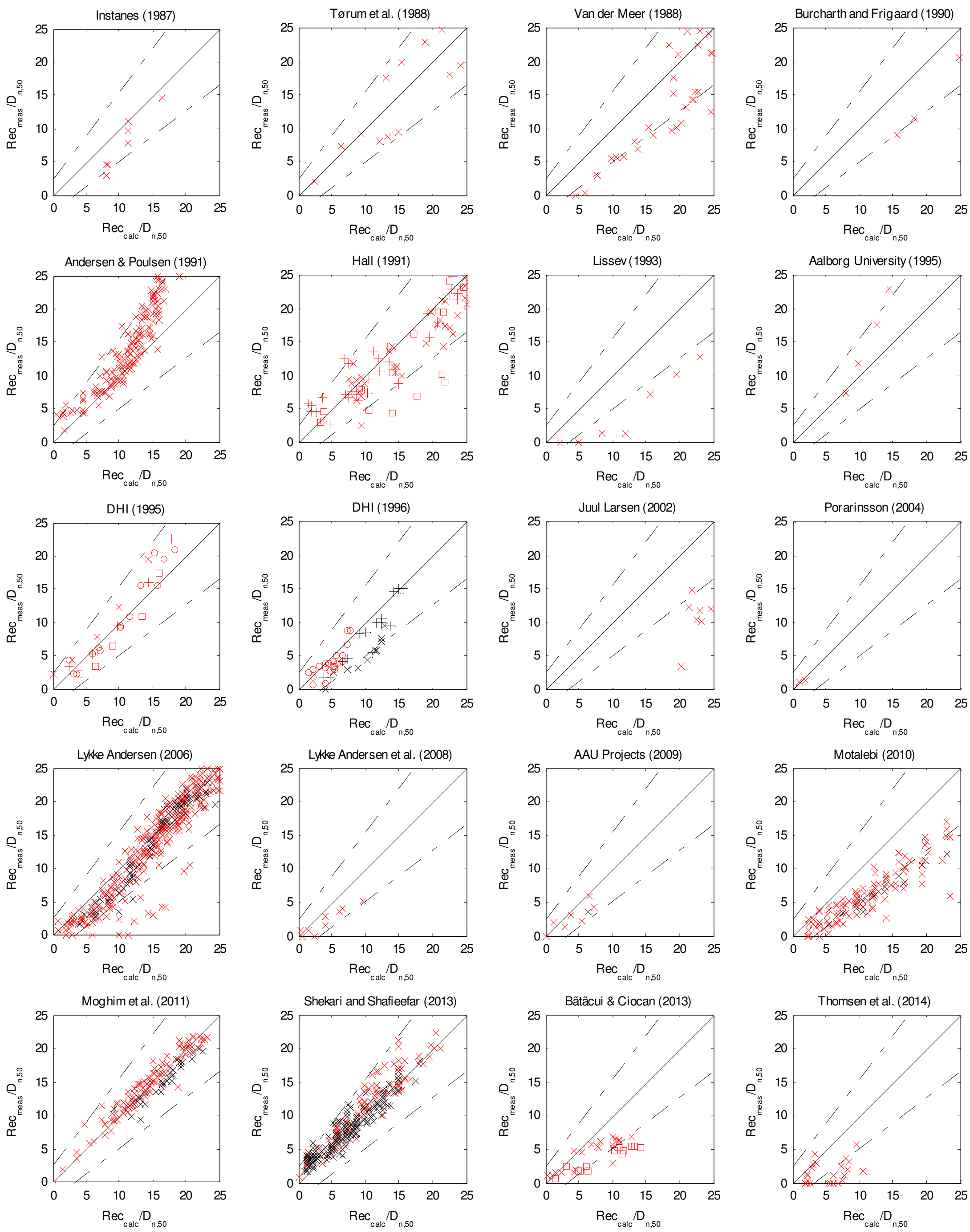

Figure 4. Evaluation of Shekari and Shafieefar (2013) formula (Eq. 4) against the database. Red points are data outside the validation area.

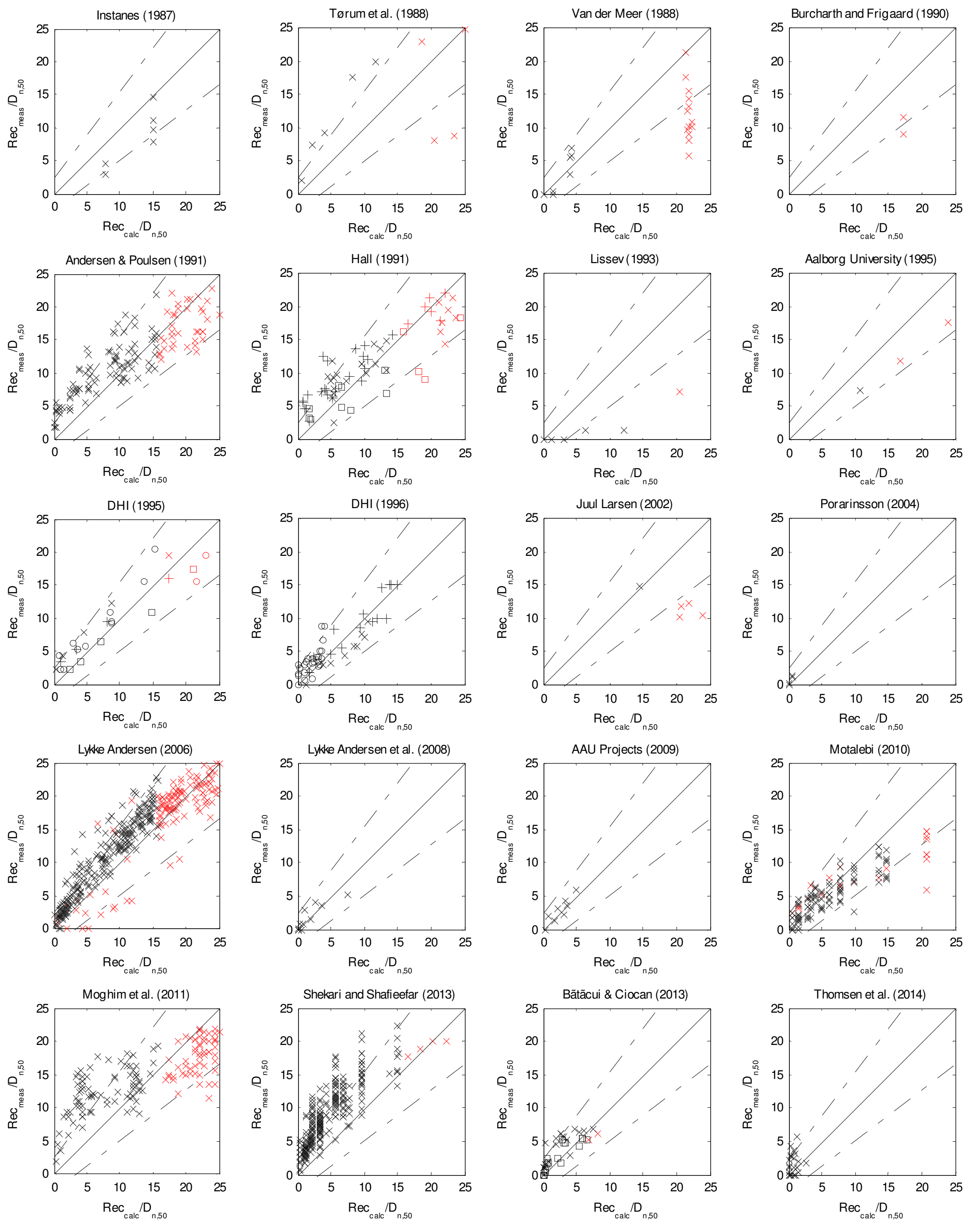

Figure 5. Evaluation of Sigurdarson and Van der Meer (2013) formula (Eq. 5) against the database. Red points are data outside the assumed validation area.

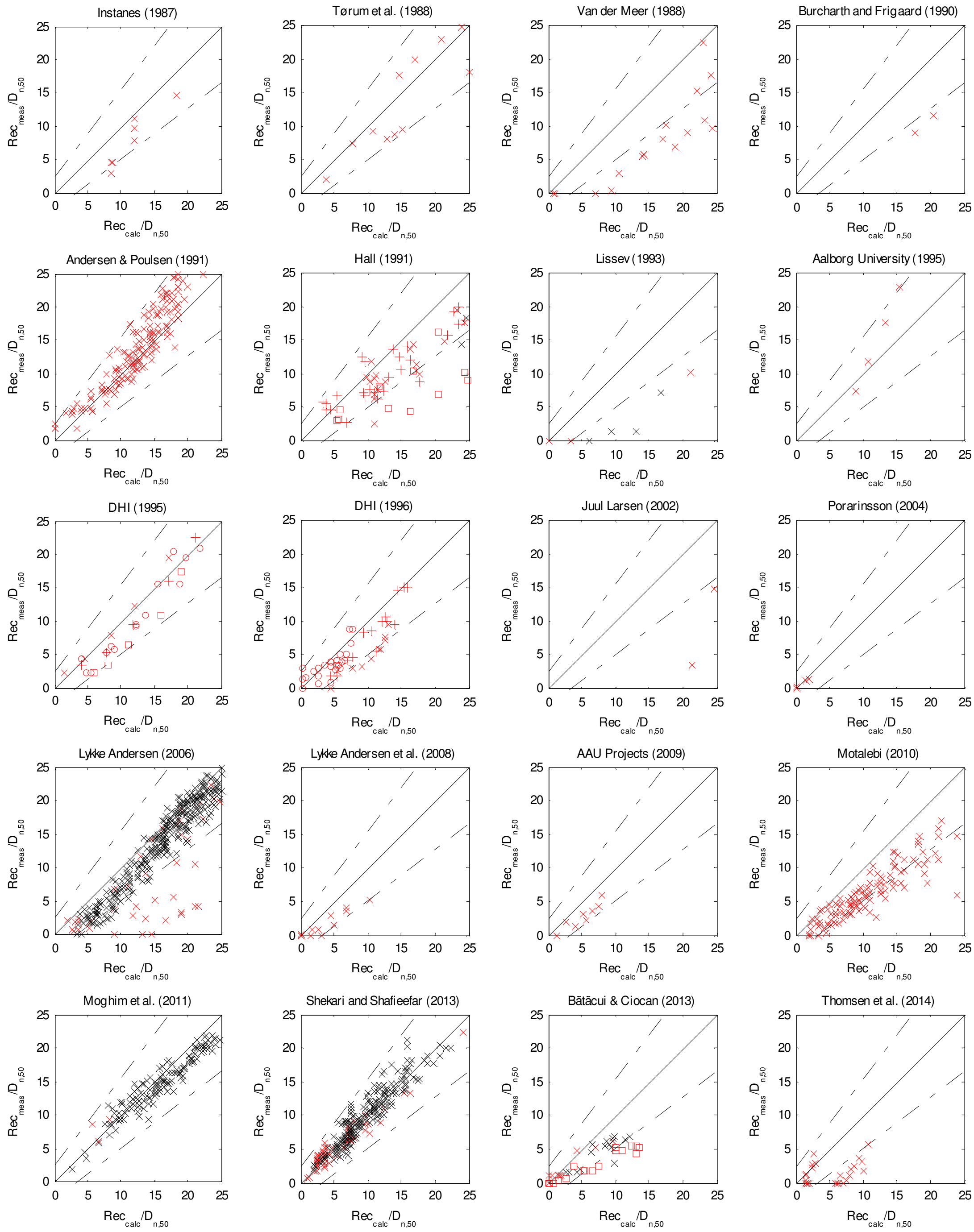

Figure 6. Evaluation of Moghim and Alizadeh (2014) formula (Eq. 6) against the database. Red points are data outside the validation area.

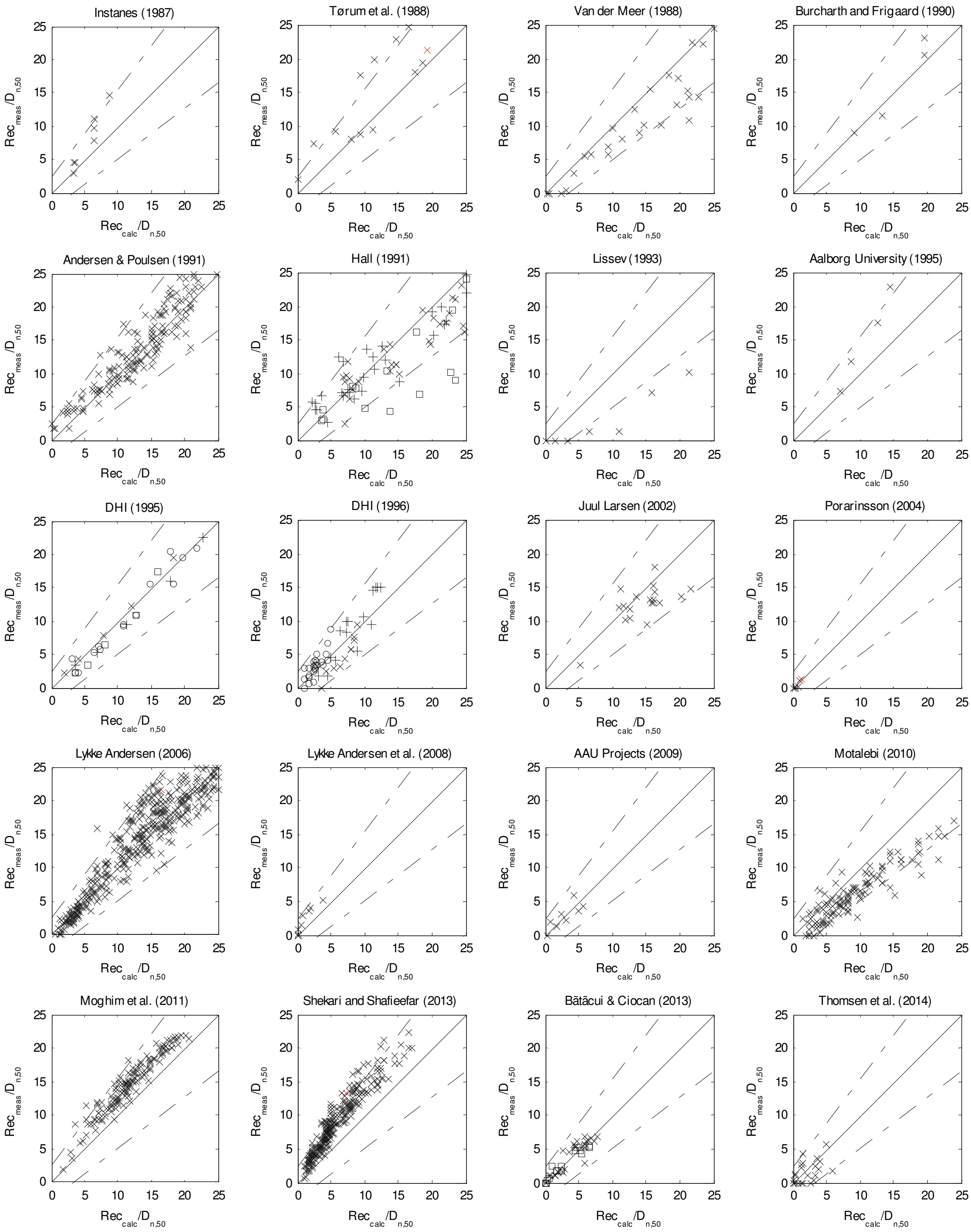

Figure 7. Evaluation of proposed updated Lykke Andersen formula (Eq. 8) against the database. Red points are data outside validation area (h_s>h).