CHAPTER 41

The Concept of Residence Time for the Description of Wave Run-Up, Wave Set-up and Wave Run-Down

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Abstract

Wave run-up, wave set-up and wave run-down are determined by using the residence time in the form of a duration curve. This method introduced by FÜHRBÖTER and WITTE (1991) considers the totality of a run-up series without considering individual run-up events separately. By using the residence time concept, wave run-up is not any more a timeless event but can be described as a time dependent variable. The results obtained by using this concept are in good agreement with previous studies based on other methods for defining wave run-up, wave set-up and wave run-down. The residence time concept has been used for regular and random waves. This concept is particularly useful for random waves, because there is no need to count the number of waves loading a dike.

1. Introduction

In the past different methods were used to define wave run-up, wave set-up and wave run-down in the swash zone. Furthermore these methods didn't consider the time the slope is covered by water during an individual run-up event. This led to the concept of the residence time developed by FÜHRBÖTER and WITTE (1991) which allows to define wave run-up, wave set-up and wave run-down. FÜHRBÖTER and WITTE verified this concept for a 1:6 slope and for wave run-up. But the concept of the residence time also allows to obtain results for wave

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set-up and wave run-down. Therefore, the concept of the residence time has been verified with a more extensive amount of data obtained from tests in the Large Wave Flume of Hannover for different slope steepnesses as well as for composite slopes. First results are presented in this paper.

Results for shock pressures obtained by the same tests are reported by GRÜNE and BERGMANN (1994).

2. Experimental Set-Up and Test Conditions

Results of wave run-up tests in the Large Wave Flume (GWK) in Hannover, Germany, for dikes and similar structures are presented. These tests were carried out for uniform slopes with steepnesses of 1:6 and 1:12 as well as for composite slopes with a steepness of 1:3 for the lower slope and with a steepness of 1:6 for the upper slope (Fig. 1). A slope steepness of 1:6 was selected because it corresponds to the steepest slope recommended for seadikes in Germany (EAK, 1993). The composite slopes can be characterized by the elevation of the front edge d_k and the water depth d:

1.) position of the front edge d_k=3.3m, water depth d=4.0m
2.) position of the front edge d_k=3.3m, water depth d=5.0m
3.) position of the front edge d_k=4.5m, water depth d=4.0m
4.) position of the front edge d_k=4.5m, water depth d=5.0m

This yields ratios of d_k/d=0.825, 0.660, 1.125 and 0.900 for the composite slopes. For the two uniform slopes the water depth was d=5.0m. The slopes in the wave flume were composed of an asphalt concrete layer covering a sand core. For these experiments a wave run-up gauge was used (GRÜNE, 1982). All the tests were carried out using PIERSON-MOSKOWITZ and JONSWAP wave spectra covering a range between H_S/L_0=0.001 and H_S/L_0=0.031 (H_S = significant wave height, L_0 = deep water wave length).

3. The Concept of the Residence Time

Wave run-up and wave run-down occur in the swash zone (Fig. 2). The highest point represents the maximum wave run-up and the deepest point the maximum wave run-down. The elevation of the mean water level (MWL) over still water level (SWL) at the dike is defined as the maximum landward wave set-up. These three processes are described below using the residence time concept.

The wave run-up on a slope can be given as a function of time. The run-up height can be found by the difference between the highest run-up level on the slope and the mean water level (MWL) using common methods like a crest to crest, a trough

to trough or an upcrossing method. The wave run-up is treated as a time dependent event. The time during which a step on the slope is covered by water provides the loading time and the time of overtopping can be derived.

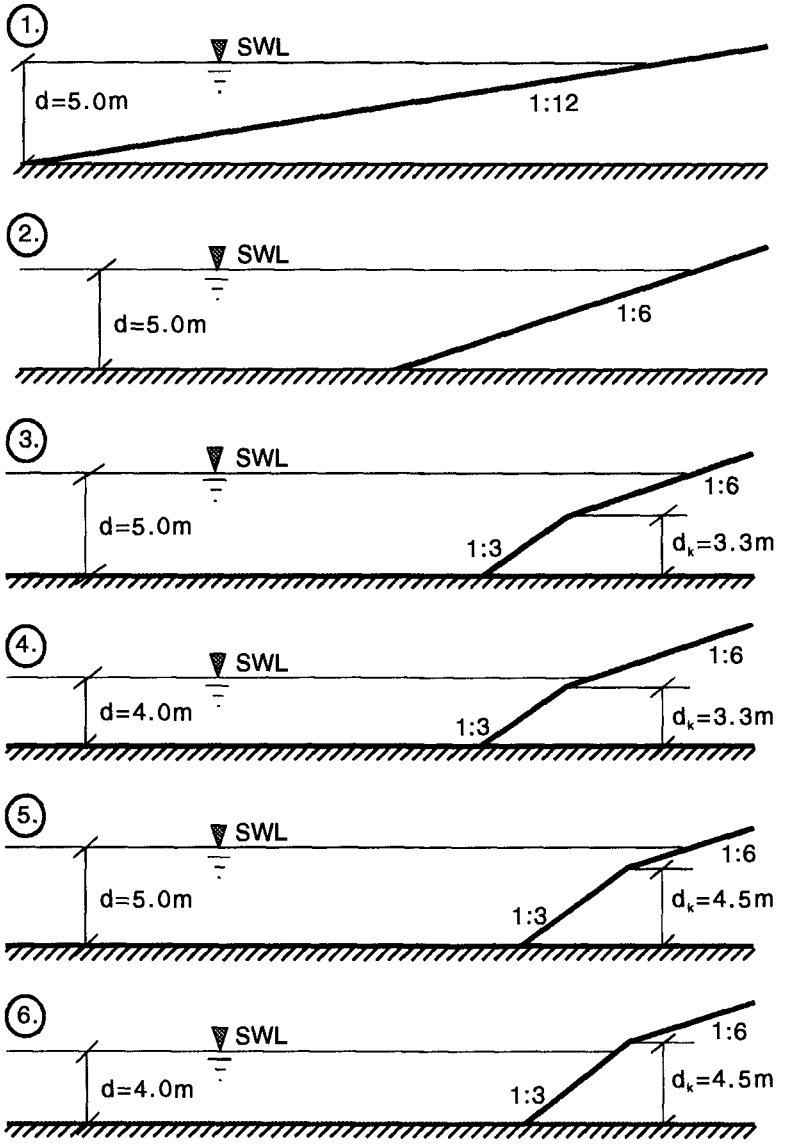

Fig. 1: Slope Configuration of the Model Dikes

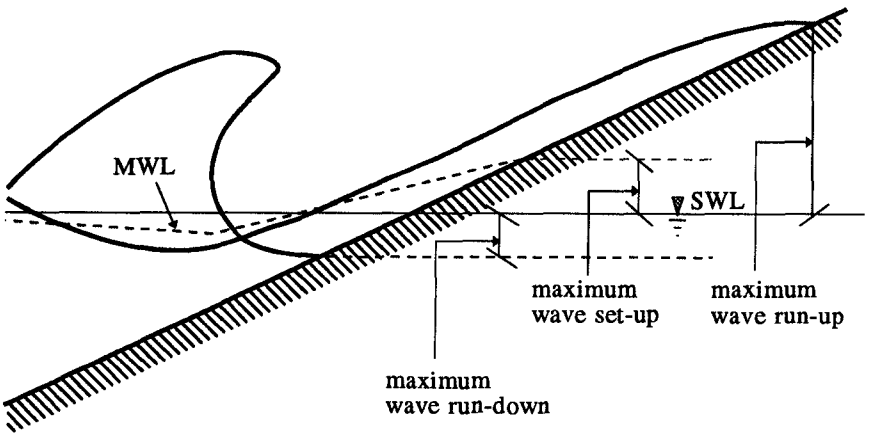

Fig. 2: Swash Zone - Definition Sketch -

The concept of residence time is illustrated by Fig. 3. In the left part the wave run-up is plotted versus time. The maximal wave run-up and the maximal wave run-down can easily be found. The time $\Delta t(r)_i$ during which a fixed step on the slope is covered by water can be calculated for each wave run-up i. The sum of the individual times $\Delta t(r)_i$ leads to the percental residence time D_r for each step r on the slope. The right part of Fig. 3 shows wave run-up as a function of the residence time D_r obtained by the residence time concept.

The residence time D_r can be calculated by the following equation:

$$D_r = \frac{1}{t} \left(\sum_{i=1}^{i=n} \Delta t(r)_i \right) \cdot 100 \qquad [\%] \tag{1}$$

t = total duration of the record

The residence time is limited by the extreme values D=0% and D=100%.

D=0% corresponds to the highest run-up level r(D=0%) and D=100% to the deepest run-down level r(D=100%). The points r(D=0%) and r(D=100%) are shown on Fig. 3.

In analogy to the 2% run-up exceedance level $R_{u2\%}$ (2% of the run-up events exceed this run-up height by an upcrossing method) mainly used by other authors (WASSING, 1942, FÜHRBÖTER and WITTE, 1989, VAN DER MEER and JANSSEN, 1994) a r(D=2%) run-up height is defined. The run-up level r(D=2%) is exceeded within 2% of the total duration t. The wave run-down height is indicated by r(D=98%), exceeded within 98% of the total duration. Between these two extreme values wave set-up is defined as the wave-induced vertical elevation of the mean water level (MWL) above still water level (SWL) (GOURLAY, 1992). The value r(D=50%) fits well with this definition because the method of the residence time is highly time dependent.

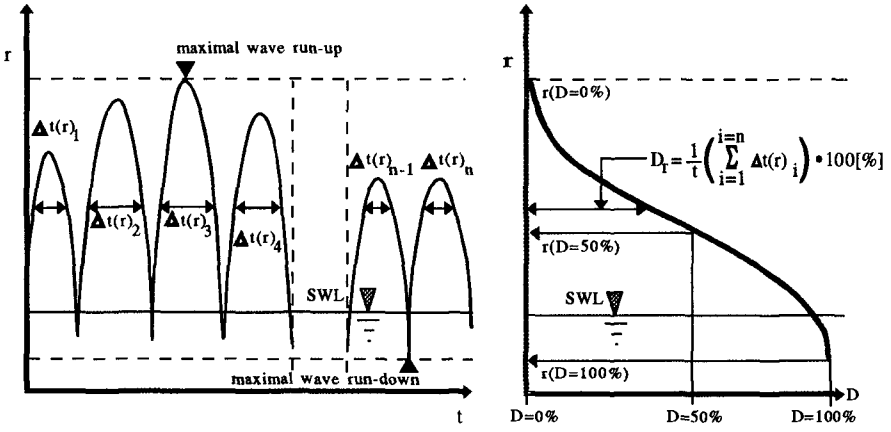

Fig. 3: Definition of the Residence Time

The difference between r(D=2%) and r(D=98%) yields the loaded area on the slope:

$$r_{AB} = r(D=2\%) - r(D=98\%) \qquad (2)$$

An example for a duration curve is shown in Fig. 4 for a composite slope with a front edge at d_K=3.3m, a water depth d=4.0m, a wave height H_S=0.75m and a wave period T_P=8.0s. Wave run-up r(D=2%), wave run-down r(D=98%) and wave set-up r(D=50%) are also indicated.

4. Wave Run-Up, Wave Run-Down and Wave Set-Up Described by the Residence Time Concept

Wave run-up, wave run-down and wave set-up are dependent on the wave parameters (wave height H_S and wave period T_p) and the slope angle α. Using the

wave steepness H_S/L_0 (H_S = significant wave height in front of the structure, L_0 = deep water wave period corresponding to T_p) and the slope angle α, the breaking wave can be described by the surf similarity parameter ξ_0 (BATTJES, 1974):

$$\xi_0 = \frac{\tan \alpha}{\sqrt{H_S / L_0}} \tag{3}$$

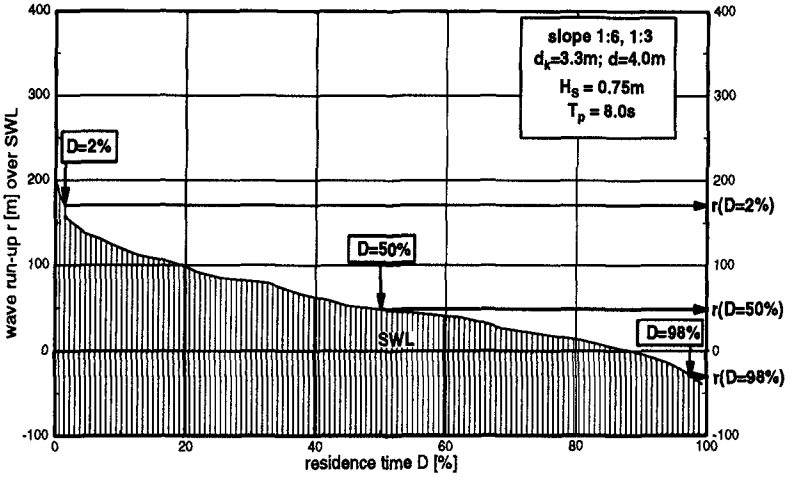

Fig. 4: The Residence Time as a Duration Curve for a Test on a Composite Slope (H_S=0.75m, T_p=8.0s)

The equivalent slope angle α' for the composite slopes is calculated using SAVILLE's method (SAVILLE, 1958) which has been verified by several authors (e.g. MAYER and KRIEBEL, 1994). This leads to an equivalent surf similarity parameter ξ_{eq} for composite slopes.

$$\xi_{eq} = \frac{\tan \alpha'}{\sqrt{H_S / L_0}} \tag{4}$$

Relative wave run-up $r(D=2\%)/H_S$, relative wave run-down $r(D=98\%)/H_S$ and relative wave set-up $r(D=50\%)/H_S$ can be related to the surf similarity parameter ξ_{eq} by using the following expression:

$$\frac{r(D)}{H_S} = A + C \cdot \xi_{eq}^{E} \tag{5}$$

A, C, E = coefficients

Fig. 5 shows a synopsis of the results for relative wave run-up, relative wave run-down and relative wave set-up versus surf similarity parameter ξ_{eq}.

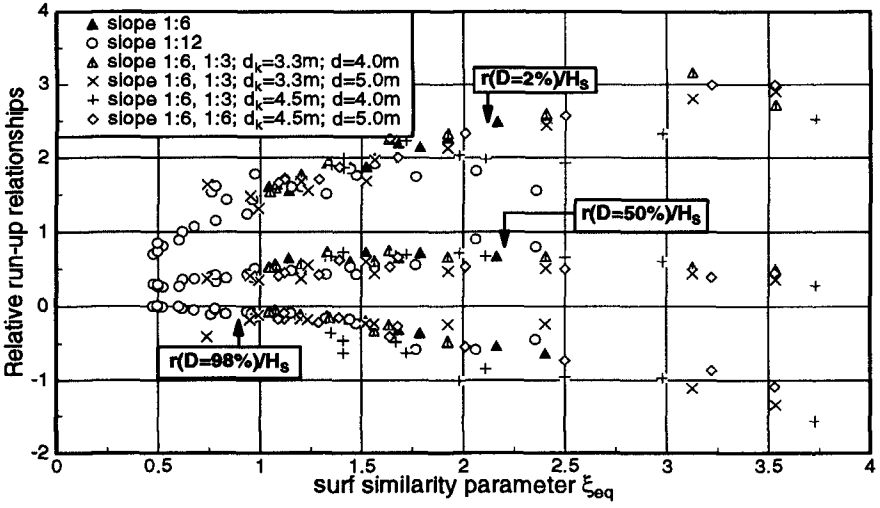

Fig. 5: Wave Run-up, Wave Set-up and Wave Run-down for Smooth Uniform and Composite Slopes

Wave Run-up

A large number of contributions to wave run-up have been published in the past. In most of them the recommended design formulas are extensions of the wave run-up formula proposed by HUNT (1959). Extensive studies were carried out in the Netherlands by VAN DER MEER and JANSSEN (1994) for uniform and composite slopes who suggested the following formula:

$$\frac{R_{u2\%}}{H_S} = 1.5\ \xi_{eq} \tag{6}$$

with a maximum relative run-up height of 3.0.

By using the concept of residence time wave run-up becomes smaller due to the slightly different definition of wave run-up. Wave run-up can be calculated by

$$\frac{r(D=2\%)}{H_S} = 1.44\ \xi_{eq} \tag{7}$$

for small surf similarity parameters $\xi_{eq}<1.0$ (Fig. 6).

For $\xi_{eq}>1.0$ relative wave run-up can be expressed by the following formula:

$$\frac{r(D=2\%)}{H_S} = 1.44 + 0.75\ (\xi_{eq}-1.0) \tag{8}$$

It can be seen that equations (7) and (8) lead to smaller wave run-up heights than equation (6) by VAN DER MEER and JANSSEN (1994). Therefore the ratio $r(D=2\%)/R_{u2\%}$ is plotted against surf similarity parameter ξ_{eq} in Fig. 7. The average deviation is about 15% with an increasing difference for higher surf similarity parameters ($\xi_{eq}>1.0$) and a smaller difference for smaller surf similarity parameters ($\xi_{eq}<1.0$).

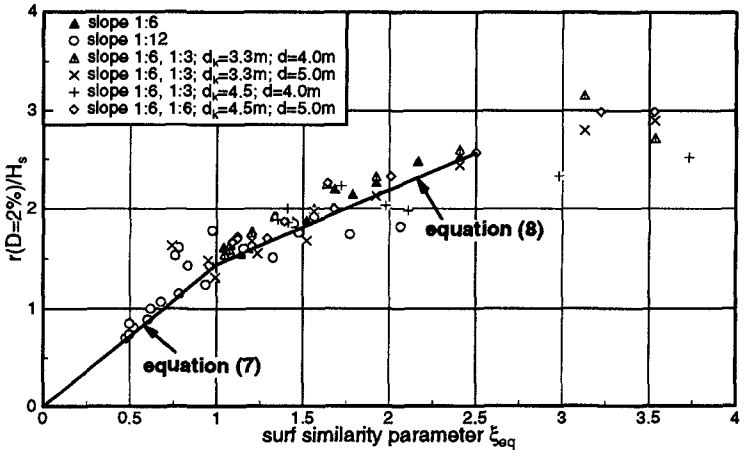

Fig. 6: Wave Run-up on Smooth Slopes

Wave Set-up

For wave set-up in the swash zone most of the known studies were performed for very smooth slopes (in GOURLAY, 1992) between $\tan\alpha=0.022$ and $\tan\alpha=0.100$.

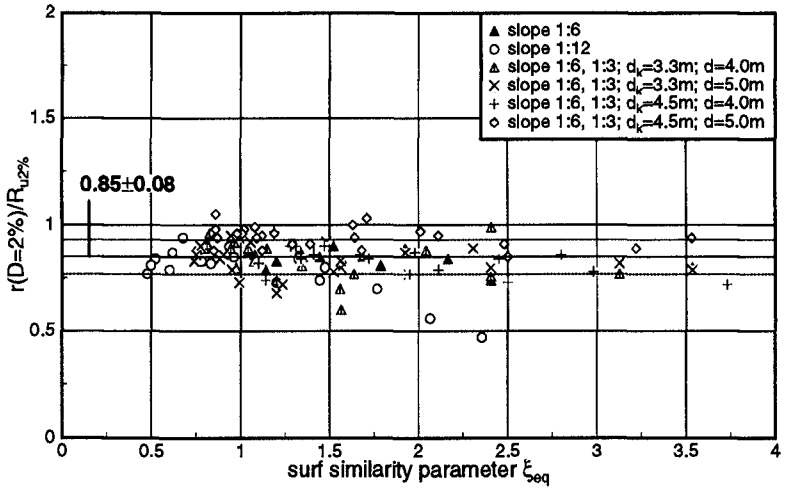

Fig. 7: Ratio $r(D=2\%)/R_{u2\%}$ versus surf similarity parameter ξ_{eq}

GOURLAY (1992) presented the following formulas for maximum set-up η_m based on field data:

$$(\eta_m-\eta_b)/H_b = 0.31 \pm 0.05 \quad \text{for } 0.083 < \tan\alpha < 0.1 \tag{9}$$

and

$$(\eta_m-\eta_b)/H_b = 0.14 \pm 0.03 \quad \text{for } 0.022 < \tan\alpha < 0.04 \tag{10}$$

η_b = Wave set-down at the breaking point

Previous studies based on field measurements by YANAGISHIMA and KATOH (1990) for a beach slope of 1:60 yield the following relationship between maximum wave set-up η_m, significant deep water wave height H_{0S} and surf similarity parameter ξ_0:

$$\frac{\eta_m}{H_S} = 0.267\ \xi_0^{0.4} \tag{11}$$

In the present paper data for relatively steep slopes between $\tan\alpha=0.083$ (1:12) and $\tan\alpha=0.333$ (1:3) are presented. Fig. 8 shows a relation between the relative wave set-up $r(D=50\%)/H_S$ and the surf similarity parameter ξ_{eq}.

For $0.5<\xi_{eq}<2.5$ the relative wave set-up can be expressed by the following formula:

$$\frac{r(D=50\%)}{H_S} = 0.45\ \xi_{eq}^{0.56} \tag{12}$$

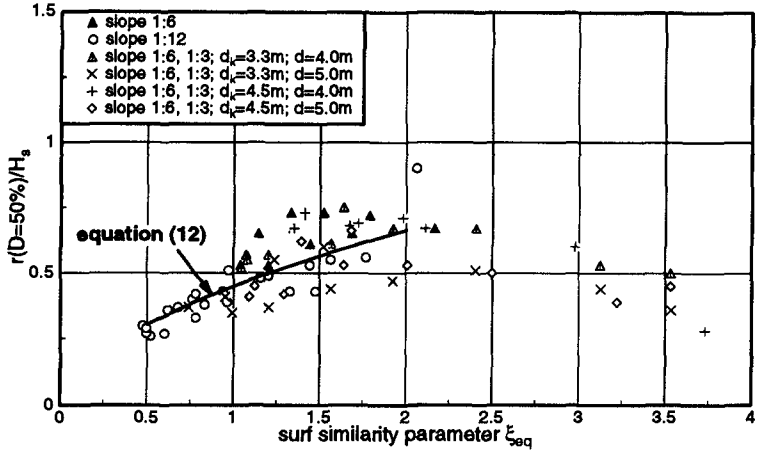

Fig. 8: Wave Set-up on Smooth Slopes

Wave Run-down

Only very few investigations on wave run-down have yet been performed. VAN DER MEER and BRETELER (1990) presented large-scale model results for wave run-down r_d on a 1:3 smooth slope and found the following relationship for similarity parameters ξ_0 in the range between 2.0 and 4.3:

$$\frac{r_d}{H} = 0.1\ \xi_0^2 - \xi_0 + 0.5 \tag{13}$$

The concept of residence time can also be used for wave run-down. The relationship between $r(D=98\%)/H_S$ and ξ_{eq} is shown in Fig. 9.

For $0.5<\xi_{eq}<2.5$ the following formula can be established:

$$\frac{r(D=98\%)}{H_S} = -0.1\ \xi_{eq}^{2.21} \tag{14}$$

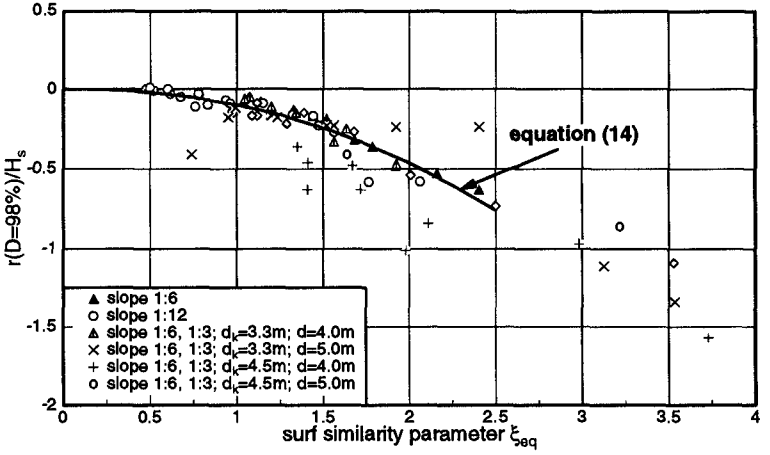

Fig. 9: Wave Run-down on Smooth Slopes

Due to a different definition of wave run-down by using the concept of residence time the obtained results are likewise smaller than the results by VAN DER MEER and BRETELER (1990).

5. Concluding Remarks

Wave run-up, wave run-down and wave set-up have been determined by using the concept of residence time in form of a duration curve. This method is highly time dependent. First results obtained by the concept of residence time have been compared to standard formulas, showing that this concept leads to:

- smaller wave run-up heights
- heigher wave set-up heights
- smaller wave run-down heights

Acknowledgements

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