1 Stability Analysis of Composite Breakwater with Wave-Dissipating Blocks
2 considering Increase in Sea Levels, Surges and Waves due to Climate Change
3

4 Hajime Mase[1]*, Daiki Tsujio[2], Tomohiro Yasuda[1] and Nobuhito Mori[1]

5

6 [1] Disaster Prevention Research Institute, Kyoto University, Gokasho, Uji, Kyoto 611-

7 0011, Japan

8 [2] Pacific Consultants Co., Ltd., 2-3-13 Azuchi-Machi, Chuo-Ku, Osaka, 541-0052,

9 Japan

10 * Corresponding author. Tel.: +81 774 38 4145; Fax: +81 774 38 4321; E-mail address:

11 mase.hajime.5c@kyoto-u.ac.jp

12

13 **Abstract:** Settlement of wave-dissipating blocks in front of a caisson is caused by

14 displacement and breakage of blocks directly by wave action and also by sliding of the

15 caisson by wave force. The settlement of blocks, caisson sliding and wave pressure are

16 mutually correlated. The present study has developed a stability analysis method for a

17 composite breakwater with wave-dissipating blocks under the circumstances of climate

18 change effect as seen in sea level rise and increase in storm surges and waves. It is

19 found that the changes of expected caisson sliding distance and necessary caisson width,

20 determined from the allowable excess probabilities for three prescribed sliding distances,

21 against the weight of wave-dissipating block have a tendency to be maximum at certain

22 block weight when repairing of damaged blocks is not done; on the other hand, if

23 repairing is done every time after reaching 5 % damage level of total section, the

24 changes of caisson sliding distance and necessary caisson width against the block

25 weight show monotonous decrease. The effects of climate change on the sliding

26 distance and necessary width are found to make those values larger 10 ~ 60 % than

27 those calculated by constant external forces given from the present climate conditions.

28

31

1. INTRODUCTION

It is pointed out that sea level rise and extremeness of tropical cyclones become noticeable in recent years due to climate change. Coastal external forces against costal defense structures, affected by the climate change, are the sea levels, storm surges and high waves. Damage of coastal structures, coastal erosion, morphological change and coastal flood disasters are expected to increase due to sea level rise and stormy wave climates. Therefore, researches of coast hazard evaluation accompanying with the change of atmosphere and ocean conditions due to climate change become important and have been carried out. The present study takes into consideration of the effects of climate change on a stability analysis of composite breakwater.

Technical Standards and Commentaries for Port and Harbour Facilities in Japan (2007) by OCDI (The Overseas Coastal Area Development Institute of Japan) provided a guideline of performance design for coastal and harbor structures. The Technical Standards shows a design method of breakwaters using partial factors based on Level I reliability analysis and allowable excess probability of a given sliding distance based on Level III reliability analysis, during a service time of the breakwater. A reliability analysis is a useful method in the performance design of various kinds of coastal structures.

Shimosako and Takahashi (2000) and Shimosako et al. (2006) and Takayama et al. (2007) proposed a performance design procedure that treats the expected sliding

52 distance of a caisson in a service time to evaluate the stability of the breakwater.

53 Shimosako et al. (2006) applied the reliability design to a breakwater armored with

54 wave-dissipating blocks, where the damage and subsidence of block section were not

55 considered. Takayama et al. (2007) extended Shimosako et al.'s method to include the

56 effect of the subsidence of block section and the resulting effect of the increase in wave

57 force due to the subsidence. There are few studies that deal with the effects of climate

58 change for the design of a caisson breakwater. Okayasu and Sakai (2006) proposed a

59 method to calculate the optimal cross section of a caisson considering sea-level rise.

60 Takagi et al. (2011) reported that the expected sliding distance for a breakwater at a

61 specific site becomes five times greater than that at present by a combination of

62 increases in sea level rise and wave height. Suh et al. (2012) described how to

63 incorporate the influence of climate change into the performance-based design. They

64 analyzed the expected sliding distance and exceedance probability of an allowable

65 sliding distance each year for the service time of the breakwater where the sea level rise,

66 deepwater wave height and storm surge (defined as 10 % of wave height) were assumed

67 to be changed as linear and parabolic manner, and showed that the effects of climate

68 change dictated in no small increase of caisson width.

69 Since there are few studies of stability analysis for a composite breakwater armored

70 with wave-dissipating blocks incorporated the changes of external forces accompanying

71 with the climate change, the present study has developed a reliability analysis of

72 estimating expected sliding distance and necessary caisson width by taking account of

73 the change of sea levels, surges and waves during a service time.

74

75 2. RELIABITY ANALYSIS OF COMPOSITE BREAKWATER WITH WAVE-

76   DISSIPATING BLOCKS

77   2.1 Modeling of Blocks' Damage

78   The following empirical formula proposed by Takahashi et al. (1998) is used to

79   estimate the degree of block damage:

80
$$N_s = \frac{H_{1/3}}{\{(\rho_s/\rho_w)-1\}D_n} = C_H\left\{a(N_0/N^{0.5})^c + b\right\} \tag{1}$$

81   where N_S = the stability number, $H_{1/3}$ = the incident significant wave height at a

82   breakwater, ρ_s = the mass density of concrete block, ρ_w = the mass density of water, D_n

83   = the representative diameter of a concrete block, C_H = the reduction coefficient for

84   wave breaking $\{=1.4/\ (H_{1/20}/H_{1/3})\}$, N_0 = the number of displaced blocks within a strip

85   width of D_n by van der Meer (1987), and N = the number of waves. The coefficients of

86   a, b and c are 2.32, 1.33 and 0.2 for Tetrapods with a 1:4/3 slope of block section. The

87   empirical formula of Eq. (1) can estimate the cumulative number of displaced blocks for

88   simulated storms by counting the number of acted waves as follows.

89   Let $N_0(i\text{-}1)$ be the cumulative number of displaced blocks up to a year ago, and

90    $H_{1/3}(i)$ and $N(i)$ be the wave height and the number of waves for a present year. The

91   equivalent number of waves, N', with $H_{1/3}(i)$ that causes $N_0(i\text{-}1)$ is obtained from Eq. (1)

92   as

93
$$N' = \left(\frac{H_{1/3}(i)/[C_H\{(\rho_s/\rho_w)-1\}D_n]-b}{a}\right)^{2/c}\{N_0(i-1)\}^2$$

94   (2)

95   By using the wave height $H_{1/3}(i)$ and the waves' number $N(i)+N'$, the cumulative

96   number of displaced blocks is calculated by

97
$$N_0(i) = \left(\frac{H_{1/3}(i)/[C_H\{(\rho_s/\rho_w)-1\}D_n]-b}{a}\right)^{1/c}\{N(i)+N'\}^{0.5} \tag{3}$$

98 for the present year's storm wave. Eqs. (2) and (3) provide the cumulative number of

99 displaced blocks.

100 The subsidence of the crown height of block section is calculated from the

101 volume of displaced blocks corresponding to the cumulative number of displaced blocks

102 that assumed to be moved seaward.

103

104 2.2 Wave Force on Caisson with Wave-Dissipating Blocks

105 In addition to the subsidence of crown height of block section directly displaced

106 by waves, it is assumed that the subsidence of the crown height is induced so as to fill

107 the space volume between the original back-face location of block section and front-

108 face location of the moved caisson. The subsidence of the crown height of block section

109 intensifies wave force acting on the caisson. Takahashi et al. (2000) proposed a method

110 to estimate the wave pressures for partially armored breakwaters that become

111 insufficient to cover the caisson by the displacement of blocks. They assumed three

112 regions where the intensity of impact wave pressure is different each other. Figure 1

113 shows a sketch of composite breakwater with wave-dissipating blocks. Impulsive wave

114 pressures act in Region 1 and 2 when the caisson is un-armored and the modification

115 coefficients to Goda's formula (2000) was proposed. Wave pressures in Region 3 are

116 estimated by Goda's formula (2000). Since the modification coefficients for Region 1

117 and 2 by Takahashi et al. (2000) are lengthy, they are not described here. Figure 2

118 shows the change of wave pressure distributions from fully armored state to partially

119 exposed state, in which the increase in wave pressures is seen in Region 1 and 2.

120   The time variation of wave pressure is given by the method by Tanimoto et al.

121   (1996) in which standing wave pressure, double peak pressure, wave breaking pressure

122   and impulsive wave pressure were modeled.

123   The armor concrete blocks are moved and settled down by storm waves. Their

124   damage and subsidence intensify wave pressures on the caisson. Those intensified wave

125   pressures promote the sliding of the caisson; the caisson sliding also makes the crown

126   height set down, and furthermore intensifies wave pressures. In this study, the repairing

127   of block section is carried out when the damage level to the total section reaches 5%;

128   that is, the crown height of blocks is reset at the original position.

129

130   2.3 Reliability Analysis of Level III

131   The sliding distance is calculated from the wave forces. The mathematical model to

132   calculate the sliding distance is seen many papers (e.g., Shimosako and Takahashi,

133   2000; Goda and Takagi, 2000; Goda, 2001; Kim and Takayama, 2003; Hong et al.,

134   2004, Suh et al., 2012). The present study followed the existence procedure for

135   calculation of sliding distance by the wave forces. The routine of estimating the

136   subsidence of crown height of block section and the change of wave forces due to

137   insufficient armor is added to the existing procedure.

138   In a reliability analysis of Level III, probability density functions (pdfs) of

139   random variables are used to calculate a failure probability. The Monte-Carlo

140   simulation is employed to give individual random values from the target pdfs. Although

141   the present study does not use the failure function, the simulation procedure is the same

142   as the reliability analysis. Figure 3 shows a flowchart to compute each sliding distance

143 and expected sliding distance (average of repetition results) of caisson during a service

144 time; 50 years is taken as the service time.

145   The flow using the Monte-Carlo simulation is as follows:

146 1. Setting of annual maximum wave from a given extreme distribution function

147 2. Calculation of wave height $H_{1/3}$ at a target breakwater location

148 3. Generation of individual waves from the Rayleigh distribution with $H_{1/3}$

149 4. Calculation of total sliding distance in a storm; at the same time, the damage degree

150 and settlement are calculated for $H_{1/3}$

151 5. Calculation of cumulative slide distance and settlement of concrete blocks

152 6. Modification of wave pressures due to settlement of blocks

153 7. Procedures from 1 to 6 are repeated for service time

154   By repeating the above flow 10,000 times, the expected sliding distance of a

155 caisson and excess probability of a specific sliding distance are obtained.

156

157 3. SETTING OF EXTERNAL FORCES

158 3.1 Sea Level Rise (SLR)

159   The influences of global climate change due to greenhouse effects will be noticeable

160 in recent years. The sea level rise is static issue of climate change and is important for

161 human activity near the coastal zone. A global sea level increased by 1.8mm/year from

162 1961~2003 and 3.1mm/year from 1993~2003 (IPCC, 2007), and IPCC AR4 denotes

163 that the projected maximum and minimum sea level rise at the end of 21st century are

164 0.18m and 0.59m depending on different scenarios and general circulation model

165 outputs.

166   On the other hand, it is not appropriate using the global value for regional impact

167   assessment. Mori (2012) and Mori et al. (2013) summarized the sea level rise by

168   arranging all available CMIP3 models for A2, A1B and B2 scenario around Japan.

169   Figure 4 shows Japan region outputs from CMIP3 for A1B scenario. The mean SLR

170   trend around Japan is slightly different from the global trend, and the standard deviation

171   between the models is two times larger than that of global value (Mori et al., 2012). The

172   present study uses the ensemble mean value of 0.26 mm/year for the sea level rise

173   around Japan.

174

175   3.2 Storm Surges

176   Projection of future change of storm surges is difficult due to the randomness of

177   typhoon occurrence and strong dependence of typhoon track (e.g. Mori, 2012). There

178   are several studies to project regional future storm surges accompanying with the

179   change of typhoon characteristics (e.g., Kawai et al., 2007, 2009; Yasuda et al., 2009).

180   Since Kawai et al. (2007) showed how storm surge heights will change corresponding to

181   future typhoons under A2 scenario, the present study followed the result by Kawai et al.

182   (2007). Figure 5 displays the occurrence probability density functions of surge heights

183   at Osaka Bay, Japan, in present climate and future climate at the end of 21st century.

184   The pdfs, shown below, are used as the extreme distributions in this study.

185
$$F(x) = 1 - \exp\left\{ -\left(\frac{x+0.248}{0.998} \right)^{1.4} \right\} \qquad ; \text{ for present climate} \qquad (4)$$

186
$$F(x) = \exp\left[-\exp\left\{ -\left(\frac{x-0.358}{0.646} \right) \right\} \right] \qquad ; \text{ for future climate} \qquad (5)$$

187

188   3.3 Storm Waves

189   Mori et al. (2010a, 2010b) investigated future ocean wave climate in comparison

190   with present wave climate based on an atmospheric general circulation model and

191   global wave model under A1B scenario. They showed that future change of averaged

192   wave height depends on latitude strongly. On the other hand, the extreme wave height in

193   the future climate will increase significantly in tropical cyclone prone areas. They also

194   provided extreme distributions of wave heights in summer and winter season,

195   considering the different weather systems, by using the peak over threshold approach

196   (POT). The POT approach counts maximum values of each storm event and it is

197   possible to increase the number of events rather than annual maximum. The storm is

198   defined as the sequence of values exceeding a certain high threshold. The estimated

199   statistical extreme distributions are shown in Fig. 6 (a) for summer season and Fig. 6 (b)

200   for winter season; those are described by

201    $$F1(x) = 1 - \exp\left\{-\left(\frac{x - 7.74}{4.02}\right)^{1.0}\right\} \quad ; \quad \text{for summer season in present climate} \qquad (6)$$

202    $$F2(x) = 1 - \exp\left\{-\left(\frac{x - 5.72}{1.80}\right)^{1.4}\right\} \quad ; \quad \text{for winter season in present climate} \qquad (7)$$

203    $$F1(x) = 1 - \exp\left\{-\left(\frac{x - 7.58}{5.25}\right)^{1.0}\right\} \quad ; \quad \text{for summer season in future climate} \qquad (8)$$

204    $$F2(x) = 1 - \exp\left\{-\left(\frac{x - 6.03}{1.26}\right)^{1.0}\right\} \quad ; \quad \text{for winter season in future climate} \qquad (9)$$

205   The cumulative distribution for two mixed populations is given by

206    $$F(x) = \exp\left\{-\sum_{j=1}^{2}[1 - F_j(x)]\right\} \qquad (10)$$

207 where $F(x)$ is the cumulative distribution of annual maxim and $F_j(x)$ is that for summer

208 and winter seasons' extreme distributions. By using Eq. (8), Random variable can be

209 generated in the Monte-Carlo simulation.

210

211 3.4 Change of External Forces during Service Time

212   The values of sea level rise, surge heights and wave heights are assumed to

213 change linearly from the present climate and to the future one:

214 $$H(p) = H_p(p) + \frac{y}{Y}\left[H_f(p) - H_p(p)\right] \qquad (11)$$

215 where $H_p(p)$ is the value with the occurrence probability of p in the present climate,

216 $H_f(p)$ the value in the future climate, Y is set to 100 (years) and y is the passage year.

217 Though there are several choices of time trend as linear, exponential, and quadratic

218 increase, the present study adopted only the linear increase. This choice may larger

219 impact compared to the other choices. In addition to the time trend, there are many

220 factors which affect the results: different GCM outputs under different scenarios. The

221 present study used a GCM projection by Meteorological Research Institute (Japan

222 Meteorological Agency) under A1B scenario. The results of GCM model ensemble and

223 scenario ensemble should be examined to provide a mean values and variation, but not

224 carried out here.

225

226 3.5 Calculation Conditions

227   Table 1 shows the calculation conditions of the offshore design wave height in

228 summer and winter season for the present and future climate, the installed water depth

229 of breakwater, the design caisson width, the crown height, the storm surge height for the

230 present and future climate, the sea level rise, the duration period of one storm, the

231   service time of breakwater, the repetition number of Monte-Carlo simulation, the

232   criterion of damage level required for repairing armor blocks. Noted that the design

233   caisson width are determined by a conventional design method to have SF=1.2 (Safety

234   Factor) for the design wave at the breakwater estimated through wave transformation of

235   shoaling and wave breaking with the refraction coefficient of $K_r = 1.0$ and 0.5 in the

236   present climate where the surge height is not included. The duration time of one storm

237   is 2 hours. Each wave period was set so as to be the wave steepness of 0.033 depending

238   on each wave height. The coefficient of friction factor for sliding is given by a

239   Gaussian distribution with the mean value of 0.6 and standard deviation of 0.16.

240   The weight of blocks is changed as 16 kinds from 2 t to 80 t. Two cases are

241   analyzed without and with repairing of block section when the damage percent reaches

242   5 %. The repairing means that the crown height of blocks is reset at the original position.

243   Figure 7 shows the cross section of model breakwater used in this study.

244

245   4. RESULTS

246   4.1 Expected Sliding Distance of Caisson

247   Figure 8 shows the expected sliding distance of a caisson against the block weight

248   for three kinds of installed water depth when K_r=0.5; (a) is for 7 m, (b) 10 m, and (c) 15

249   m. In these figures, the results of expected sliding distance with and without

250   considering the climate change effects and the repairing of block section are shown by

251   different symbols. When the repairing is not done, the expected sliding distance shown

252   by solid and open circles has maximum for a certain block weight of 12 t in the case of

253   7 m water depth, 16 t in the case of 10 m water depth, and 20 t in the case of 15 m water

254   depth. The reason why being a maximum in Fig. 8 is as follow. Since when the block

255   weight is small, the damage becomes large and the settlement of blocks becomes large,

256   the regions where impulsive wave pressures act on the caisson become smaller and the

257   sliding distance becomes small. As the result there appears a maximum in the change of

258   sliding distance against the block weight; that is, sliding, settlement and pressure are

259   correlated.

260   If the repairing is done when the damage level reaches 5 %, the expected sliding

261   distance of caisson decreases with the increase in block weight except the case of

262   installed water depth 7 m and smaller block's weight than 4 t, as shown by solid and

263   open triangles.

264   When comparing the results with and without taking into consideration of climate

265   change effects, the expected sliding distances with climate change effects are 10 ~ 60 %

266   larger than those without climate change effects. The result is shown clearly in the

267   Chapter 5.

268

269   4.2 Necessary Width of Caisson

270   Figure 9 shows the necessary caisson width that satisfies the allowable excess

271   probabilities for specified sliding distances when K_r=0.5. The allowable excess

272   probabilities are denoted in Table 2 proposed by Shimosako and Tada (2003). The

273   present study adopted the values for Importance Level 2 (Ordinary). As like the

274   expected sliding distance, the necessary caisson width has the maximum against the

275   block weight; however, the block weight at the maximum caisson width is different

276   from that obtained for the expected sliding distance. Comparing the caisson width

277   determined by the conventional design method using safety factor with that by

278   performance design method using allowable distance and excess probability, the

279　conventional method gives underestimations for all three cases of installed water depths

280　7 m, 10 m and 15 m.

281

282　5. EFFECT OF CLIMATE CHANGE ON BREAKWATER STABILITY

283　　　The ratio of expected sliding distance of caisson with and without including

284　climate change effects is shown in Fig. 10 (a) where the horizontal axis is taken as the

285　normalized water depth by the wave height at the breakwater to see the effect of water

286　depth for both cases of K_r=0.5 and 1.0. When we take into consideration of climate

287　change effects such as sea level rise and increase in storm surge heights and wave

288　heights, the expect sliding distance increase 10 ~ 60 % compared to the results without

289　increase of external forces. The ratios increase as the normalized water depth becomes

290　large for the case of no-repairing, although the range is limited between 1.0 and 1.5.

291　When the water depth is large, the wave height will increase due to the climate change

292　effect since wave heights are not limited by wave breaking. The case of repairing

293　shows a little higher value of the ratio showing constant against the normalized water

294　depth.   The necessary caisson width will also increase 10 ~ 20 % in spite of no-

295　repairing and repairing, as shown in Fig. 10 (b).

296　　　The above results came from the conditions described in the Chapter 3. Since the

297　present analysis method is easily able to be modified when the information of external

298　forces accompanying with climate change and conditions of target breakwater; we can

299　estimate how the impacts of climate change on a breakwater stability are severe by

300　using updated information.

301

302　6. CONCLUSIONS

303　　　This study has analyzed the stability of composite breakwater with wave-

304　dissipating blocks, based on a reliability analysis, by estimating a sliding distance of a

305　caisson with and without considering the repairing of block section and the effects of

306　climate change such as the sea level rise, storm surge heights and wave heights. It was

307　found that the changes of expected sliding distance and necessary caisson width,

308　determined from the allowable excess probabilities for prescribed sliding distances,

309　against the weight of wave-dissipating block have a tendency to be maximum at a

310　certain block weight when repairing of damaged block section is not done; on the other

311　hand, if repairing is done after reaching 5 % damage level of total section, the changes

312　of caisson sliding distance and necessary caisson width against the block weight show

313　monotonous decrease.

314　　　When the proposed method takes into consideration of climate change effects

315　such as sea level rise and increase in storm surge heights and wave heights, the expect

316　sliding distance increase 10 ~ 60 % compared to the results without increase of external

317　forces, and the necessary caisson width will increase 10 ~ 20 %.

318

324

325　REFERENCES

326   Goda, Y., 2000.   Random seas and design of maritime structures, World Scientific

327   Publishing Co. Pte. Ltd., 443p.

328   Goda, Y., and Takagi, H., 2000. A reliability design method of caisson breakwaters with

329   optimal wave heights, Coastal Eng. J., Vol.42, No.4, pp.357–387.

330   Goda, Y., 2001. Performance-based design of caisson breakwaters with new approach

331   to extreme wave statistics, Coastal Eng. J., Vol.43, No.4, pp.289–316.

332   Hong, S. Y., Suh, K.-D., and Kweon, H.-M., 2004. Calculation of expected sliding

333   distance of breakwater caisson considering variabilityin wave direction, Coastal

334   Eng. J., Vol.46, No.1, pp.119–140.

335   IPCC., 2007. Climate Change 2007: The Physical Science Basis, Working Group I

336   Contribution to the Fourth Assessment Report of the Intergovernmental Panel on

337   Climate Change. Cambridge University Press: Cambridge, UK; 996p..

338   Kawai, H., Hashimoto, N. and K. Matsuura, K., 2007. Estimation of extreme value and

339   duration of storm surge in bays by using stochastic typhoon model, Annual Journal

340   of Coastal Engineering, JSCE, Vol.54, pp.301-305 (in Japanese).

341   Kawai, H., Hashimoto, N., Yamashiro, M. and Yasuda, T., 2009. Variation of extreme

342   storm surges with wind field model and future typhoon change in stochastic

343   typhoon simulation, Journal of JSCE, Ser. B2 (Coastal Engineering), Vol.65,

344   pp.1256-1260 (in Japanese).

345   Kim, T. M., and Takayama, T., 2003. Computational improvement for expected sliding

346   distance of a caisson-type breakwater by introduction of a doubly-truncated normal

347   distribution. Coastal Eng. J., Vol.45, No.3, pp.387–419.

348 Mori, N., T. Yasuda, H. Mase, T. Tom and Y. Oku, 2010a. Projection of extreme wave

349 climate change under the global warming, Hydrological Research Letters, Vol.4,

350 pp.15-19, doi:10.3178/HRL.4.15.

351 Mori, N., Shimura, T., Yasuda, T. and Mase, H., 2010b. Projection of extreme waves

352 under a global warming scenario, Journal of JSCE, Ser. B2 (Coastal Eng.), Vol.66,

353 pp.1231-1235 (in Japanese).

354 Mori, N., 2012. Projection of Future Tropical Cyclone Characteristics based on

355 Statistical Model, In Cyclones Formation, Triggers and Control, Nova Science

356 Publishers, Inc., 24p.

357 Mori, N., Shimura, T., Nakajo, S., Yasuda, T. and H. Mase., 2011. Multi-Model

358 Ensemble Projection of Future Coastal Environment Change under a Global

359 Warming Scenario, Special Issue, Ocean Engineering, submitted.

360 Mori, N., Shimura, T., Yasuda, T. and Mase, H. 2013. Direct projection of future

361 extreme wave climate and influence of tropical cyclone activity in the northwest

362 Pacific Ocean (submitted to J. Ocean Modelling).

363 Okayasu, A., and Sakai, K., 2006. Effect of sea level rise on sliding distance of a

364 caisson breakwater: Optimization with probabilistic design method, Proc., 30th Int.

365 Conf. Coastal Engineering, ASCE, pp.4,883-4,893.

366 Shimosako, K., and Takahashi, S., 2000. Application of deformation based reliability

367 design for coastal structures, Proc., Int. Conf. Coastal Structures 99, ASCE, pp.363–

368 371.

369 Shimosako, K. and Tada, K., 2003. Study on the allowable sliding distance based on

370 the performance design of composite breakwaters, Proc. of Coastal Eng., JSCE,

371 Vol.50, pp.766-770 (in Japanese).

372 Shimosako, K., Osaki, N. and Nakano, F., 2006. Reliability design of composite

373   breakwaters based on sliding distance, Rept. of Port and Airport Res. Inst., Vol. 45,

374   No.3, pp.1-20 (in Japanese).

375 Suh, K.-D., Kim, S.-W., Mori, N. and Mase, H., 2012. Effect of climate change on

376   performance-based design of caisson breakwater, Jour. Waterway, Port, Coastal,

377   and Ocean Eng., Vol.138, No.3, ASCE, pp.215-225.

378 Takahashi, S., Hanzawa, M., Sato, H., Gomyo, M., Shimosako, K., Terauchi, K.,

379   Takayama, T. and Tanomoto, K., 1998. Lifetime damage estimation with a new

380   stability formula for concrete blocks, Rept. of Port and Airport Res. Inst., Vol.37,

381   No.1, pp.3-32 (in Japanese).

382 Takagi, H., Kashihara, H., Esteban, M. and Shibayama, T., 2011. Assessment of future

383   stability of breakwaters under climate change, Coastal Eng. Jour., Vol.53, No.1,

384   pp.21-39.,

385 Takahashi, S., Ohki, Y., Shimosako, K., Isayama, S. and Ishinuki, K., 2000. Seawall

386   failures by Typhoon 9918 and their reproduction in wave flume experiments.

387   Technical Notes of The Port and Harbour Res. Inst., No.973, 50p. (in Japanese).

388 Takayama, T., Tsujio, D. and Yasuda, T., 2007. Estimation of expected sliding distance

389   of a caisson affected by damage of armor concrete blocks. Annual Journal of

390   Coastal Eng., JSCE, Vol.54, pp.906-910 (in Japanese).

391 Tanimoto K., Furukawa, K. and Nakamura, H., 1996. Fluid resistance force during

392   sliding of caisson and the estimation model of caisson sliding, Proc. Coastal Eng.,

393   JSCE, Vol. 43, pp.846-850 (in Japanese).

394 The Overseas Coastal Area Development Institute of Japan, 2007. Technical Standards

395   and Commentaries for Port and Harbour Facilities in Japan, 1,028p..

396   Van der Meer. 1987. Stability of breakwater armour layers – design formulae, Coastal

397   Eng., Vol.11, pp.219-239.

398   Yasuda, T., Ando, K., Mori, N. and Mase, H., 2009. Prediction and stochastic modeling

399   of future typhoon characteristics based on AGCM Projections under global

400   warming scenario, Journal of JSCE, Ser. B2 (Coastal Eng.), Vol.65, pp.1281-1285

401   (in Japanese).

402

403   Captions of figures

404   Figure 1. Three different regions regarding intensity of wave pressure

405   Figure 2. Distribution of wave pressures in fully and partially covered with blocks

406   Figure 3. Flow of estimating expected sliding distance

407   Figure 4. Sea level rise adjacent Japan seas (Mori et al., 2012)

408   (bccr: Bjerknes Centre for Climate Research; giss: NASA Goddard Institute for Space

409   Studies; miub: Meteorologisches Institut der Universitat Bonn; ukmo: UK Met

410   Office)

411   Figure 5. Probability density functions of present and future surge heights (Kawai et al.,

412   2007)

413   Figure 6. Probability density functions of extreme wave height distribution; (a) summer

414   season; (b) winter season (Mori et al., 2010)

415   Figure 7. Cross section of model breakwater

416   Figure 8. Expected sliding distance of caisson; (a) installed water depth of 7m; (b)

417   installed water depth of 10m; (c) installed water depth of 15m

418   Figure 9. Necessary caisson width; (a) installed water depth of 7m; (b) installed water

419   depth of 10m; (c) installed water depth of 15m

420   Figure 10. Effects of climate change for expected sliding distance and necessary

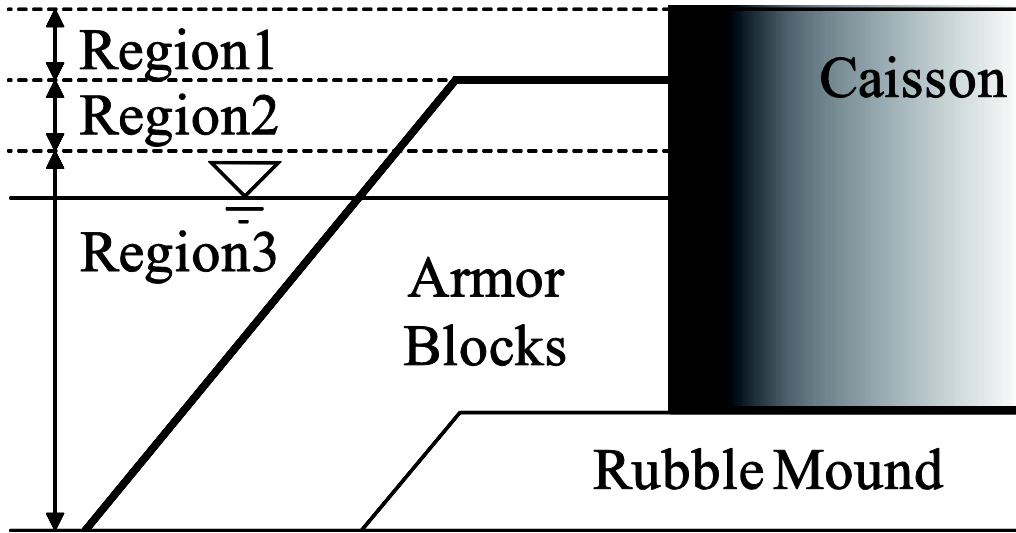421   caisson width; (a) sliding distance; (b) necessary caisson width

422

423

424

425   Caption of tables

426   Table 1 Calculation conditions

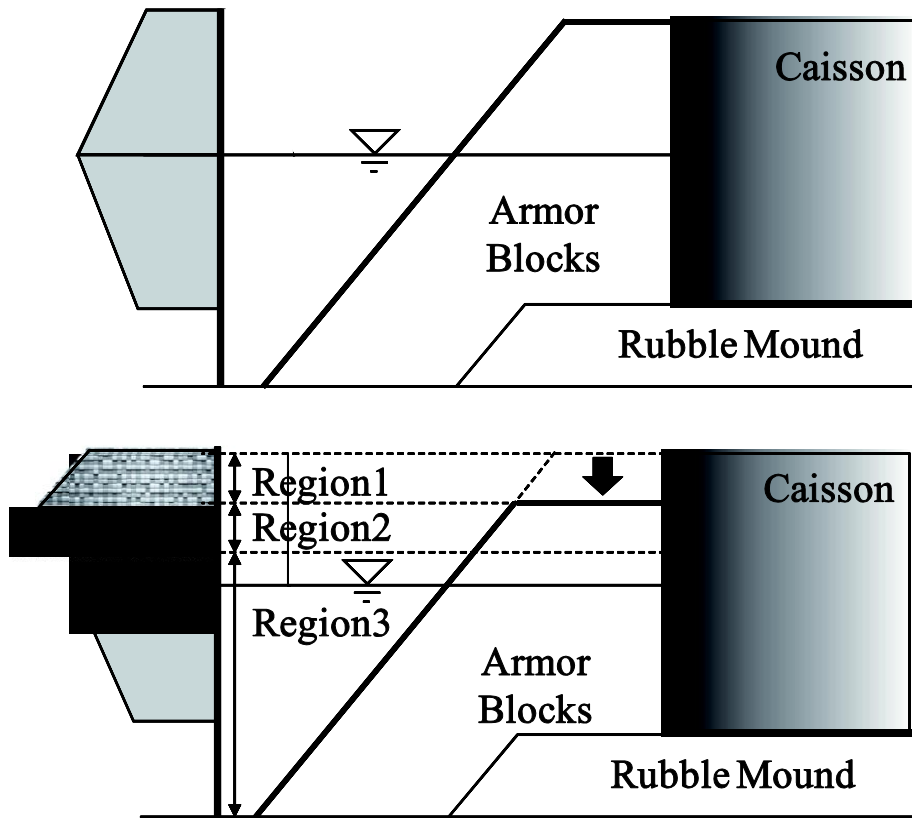427   Table 2 Allowable sliding distance and excess probability

428

Figure 1. Three different regions regarding intensity of wave pressure

434

435

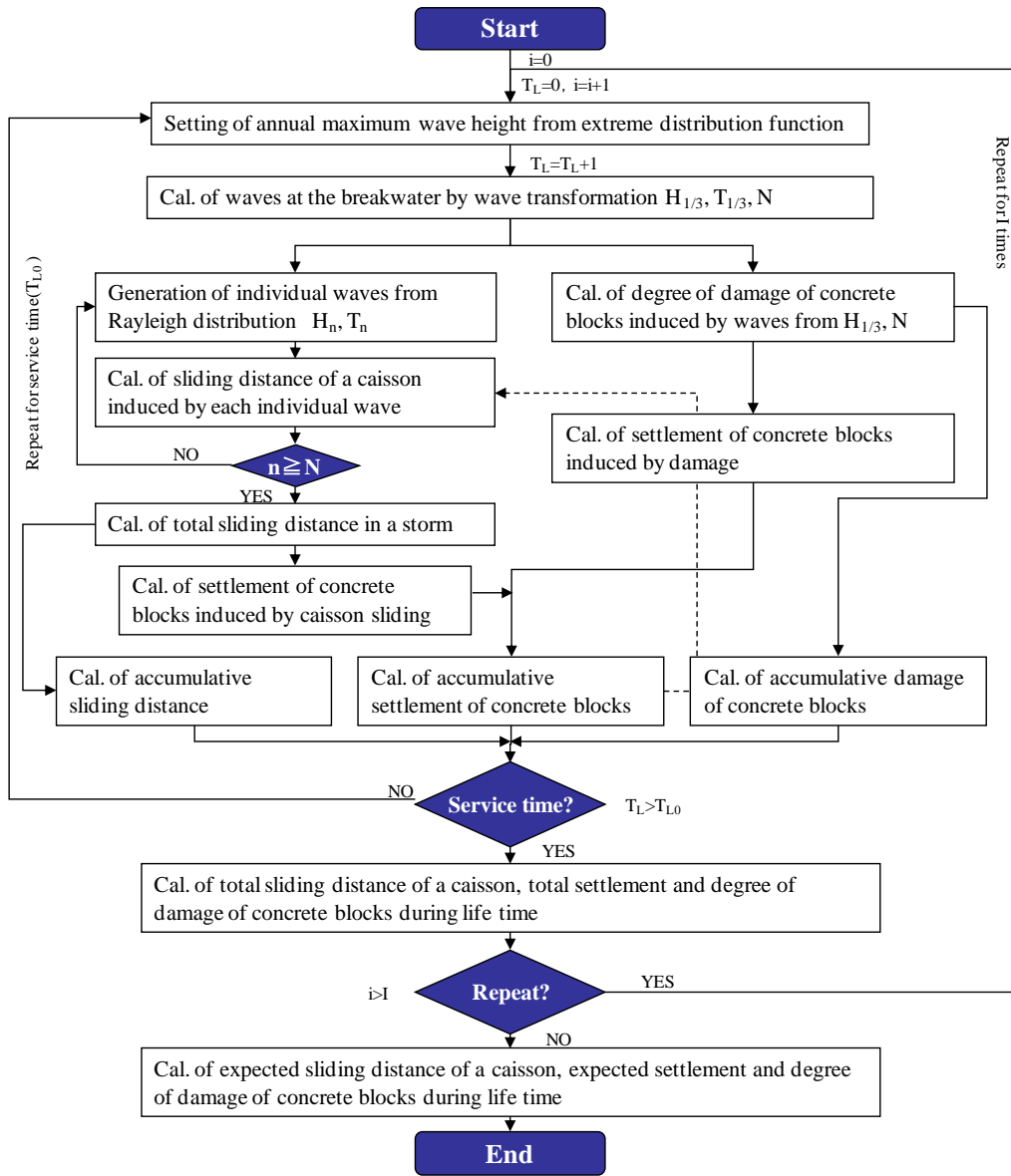Figure 2. Distribution of wave pressures in fully and partially covered with blocks
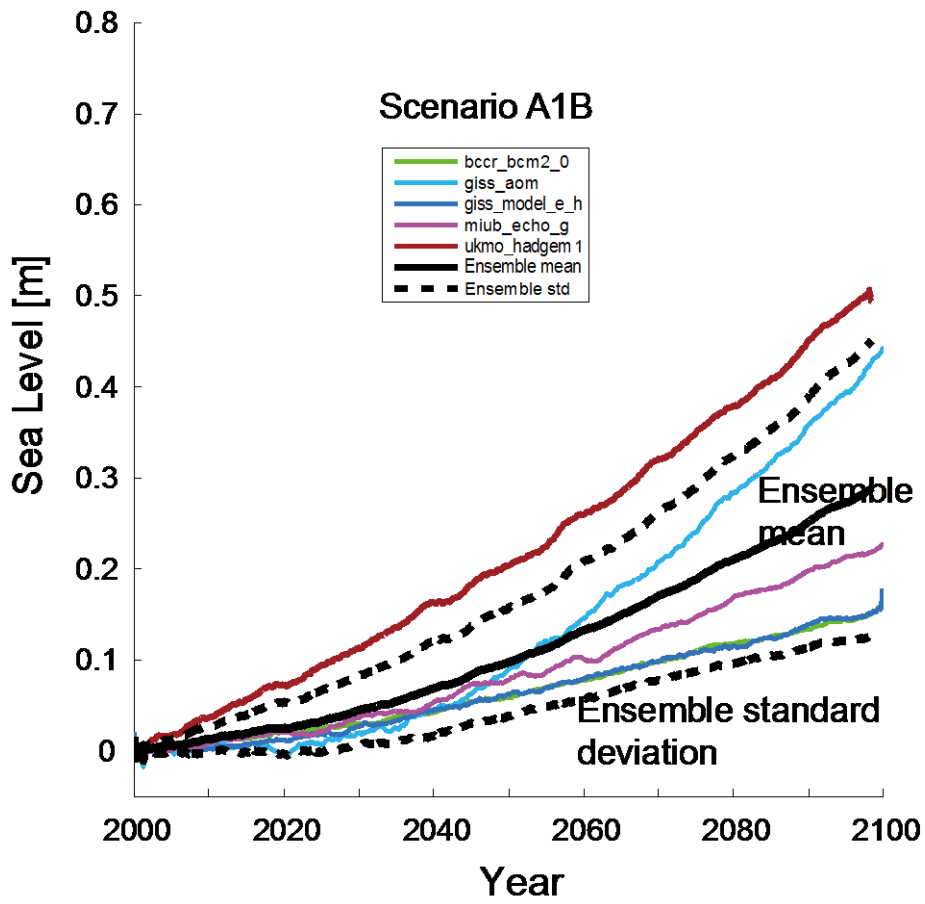
437

438

439

440

Start

i=0

$T_L=0$, i=i+1

Setting of annual maximum wave height from extreme distribution function

$T_L=T_L+1$

Cal. of waves at the breakwater by wave transformation $H_{1/3}$, $T_{1/3}$, N

Generation of individual waves from Rayleigh distribution H_n, T_n

Cal. of sliding distance of a caisson induced by each individual wave

NO

n ≧ N

YES

Cal. of total sliding distance in a storm

Cal. of settlement of concrete blocks induced by caisson sliding

Cal. of degree of damage of concrete blocks induced by waves from $H_{1/3}$, N

Cal. of settlement of concrete blocks induced by damage

Cal. of accumulative sliding distance

Cal. of accumulative settlement of concrete blocks

Cal. of accumulative damage of concrete blocks

NO

Service time?

$T_L>T_{L0}$

YES

Cal. of total sliding distance of a caisson, total settlement and degree of damage of concrete blocks during life time

i>I

Repeat?

YES

NO

Cal. of expected sliding distance of a caisson, expected settlement and degree of damage of concrete blocks during life time

End

Repeat for service time(T_{L0})

Repeat for I times

441

442

443   Figure 3. Flow of estimating expected sliding distance

444

445

Figure 4. Sea level rise adjacent Japan seas (Mori et al., 2012)

(bccr: Bjerknes Centre for Climate Research; giss: NASA Goddard Institute for Space

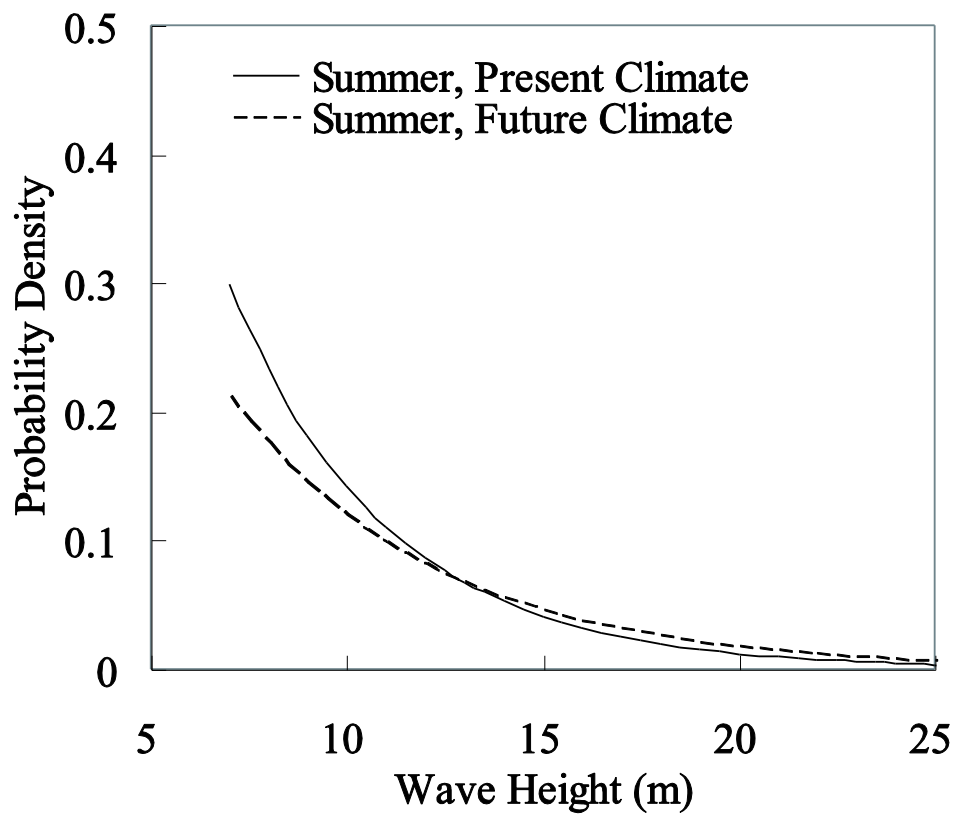Studies; miub: Meteorologisches Institut der Universitat Bonn; ukmo: UK Met Office)

454
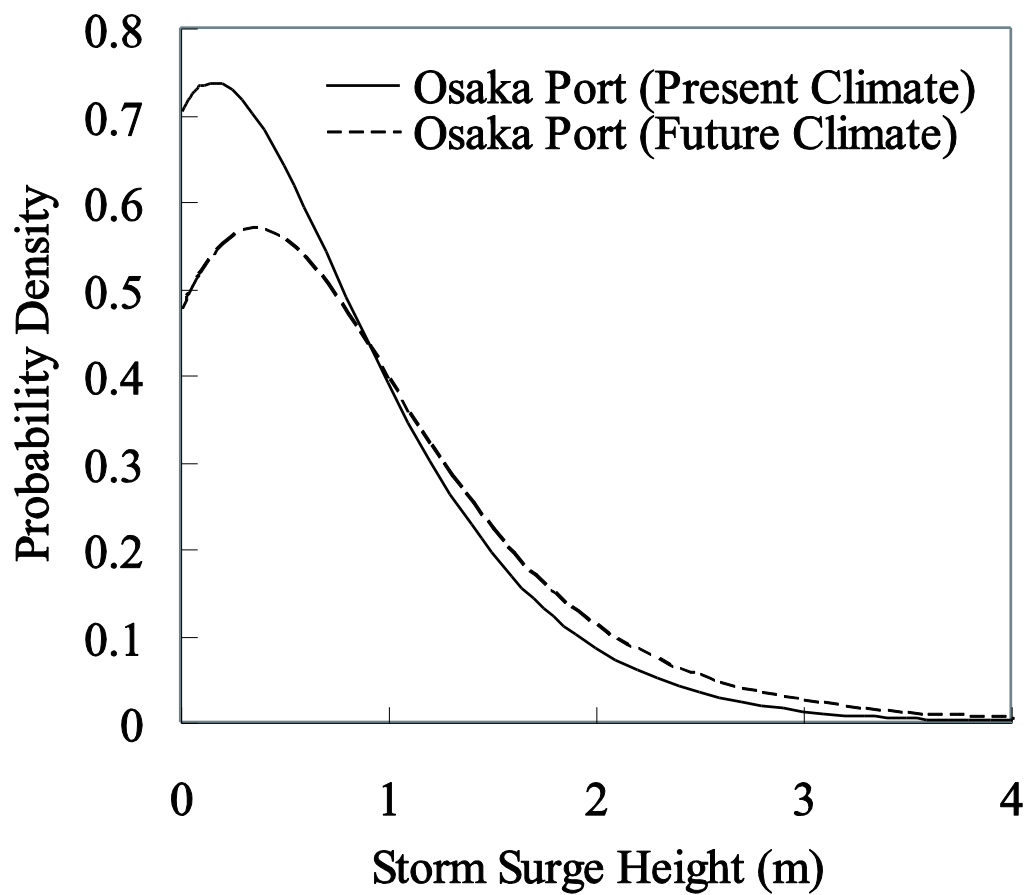
455

456

Figure 5. Probability density functions of present and future surge heights (Kawai et al.,

2007)

459

460

461

462

463   Figure 6 (a). Probability density functions of extreme wave height distribution; (a)

464   summer season; (b) winter season (Mori et al., 2010)

465

466

467

468

469
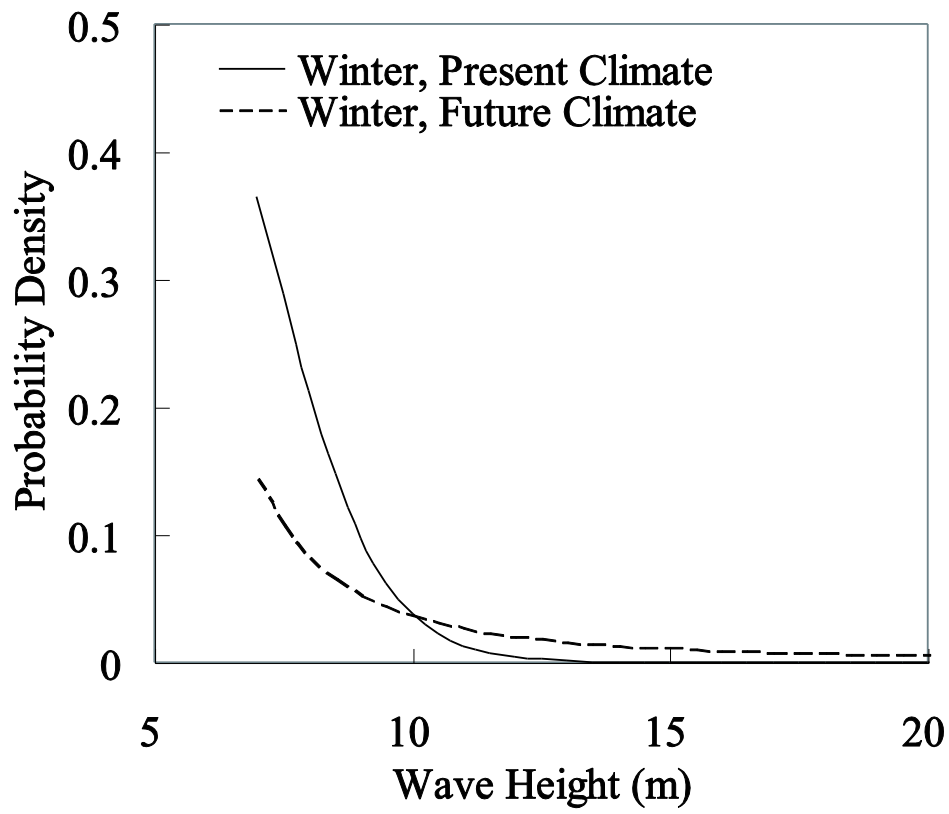
Figure 6 (b). Probability density functions of extreme wave height distribution; (a) summer season; (b) winter season (Mori et al., 2010)

Caisson Width
14.3~21.3m

Crown Height
3.8~6.8 m

Caisson

Depth
7m, 10m, 15m

Armor
Blocks
2t~80t

Rubble Mound   2m
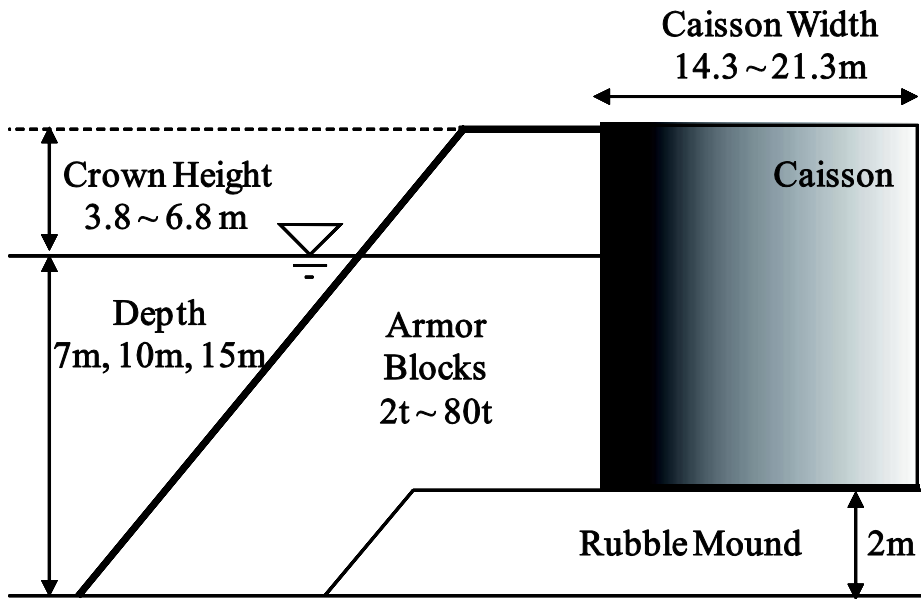
Figure 7. Cross section of model breakwater
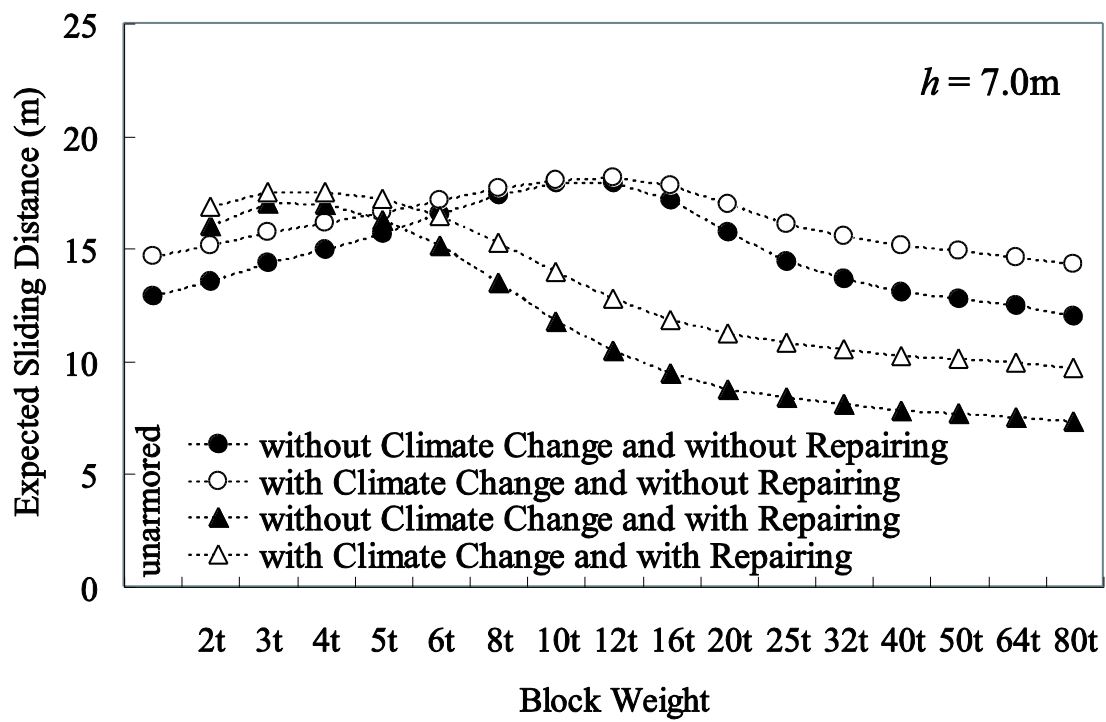
486

487

488   Figure 8 (a). Expected sliding distance of caisson

489

490

491
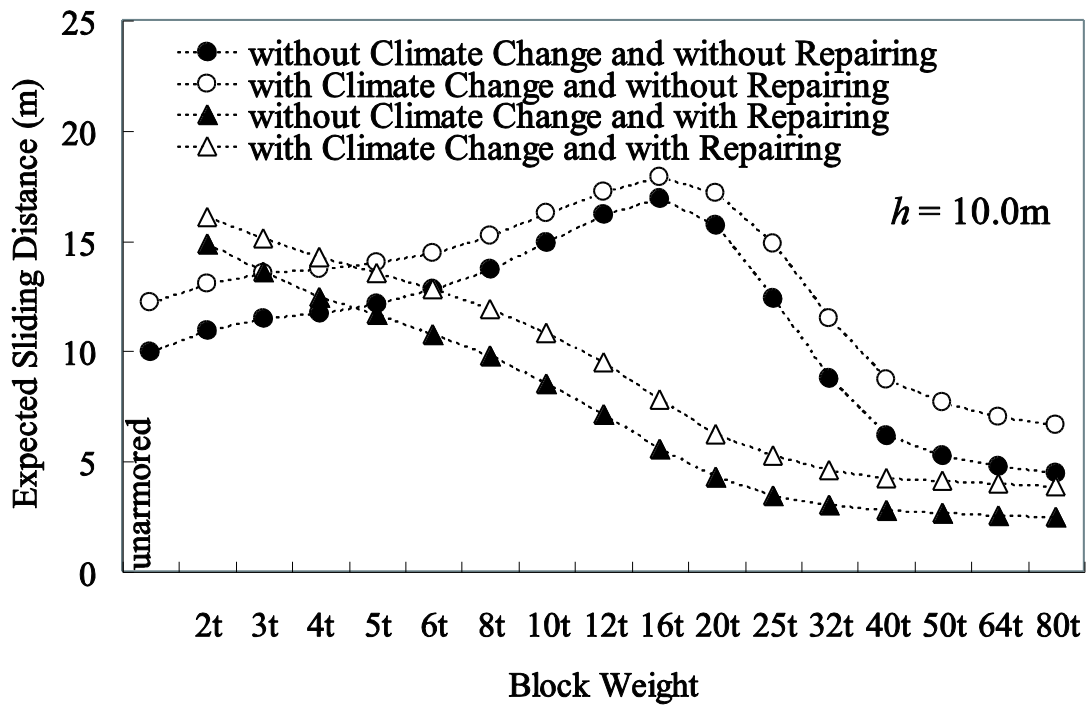
492

493

494

495   Figure 8 (b). Expected sliding distance of caisson

496

497

498

499
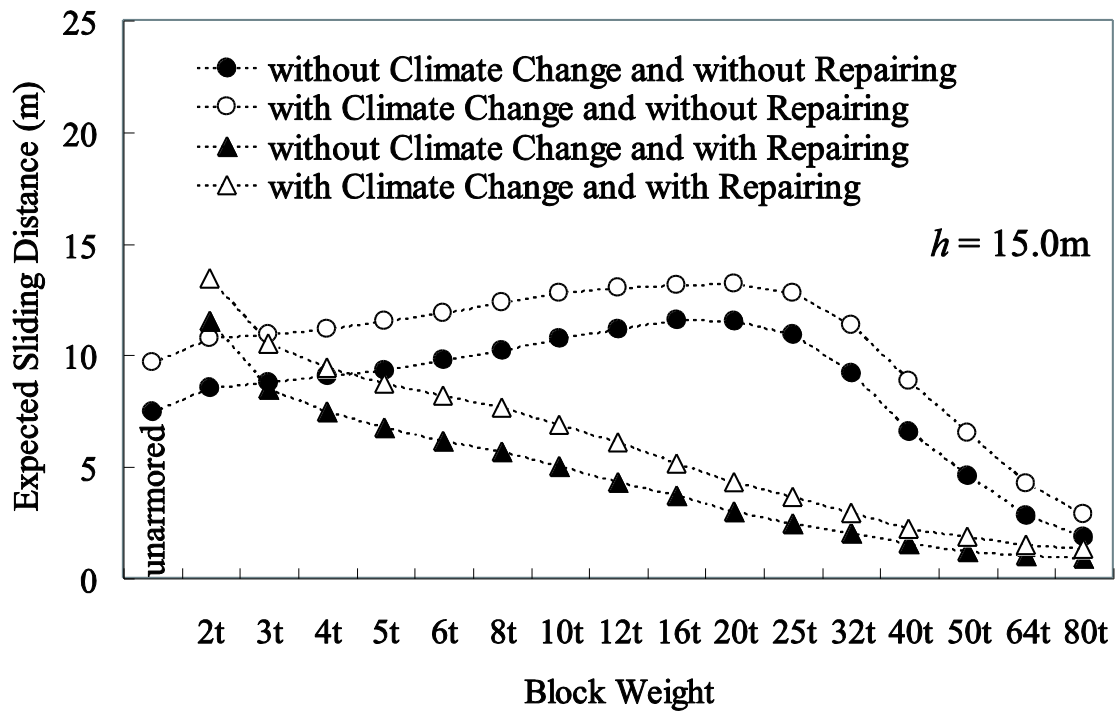
Figure 8 (c). Expected sliding distance of caisson
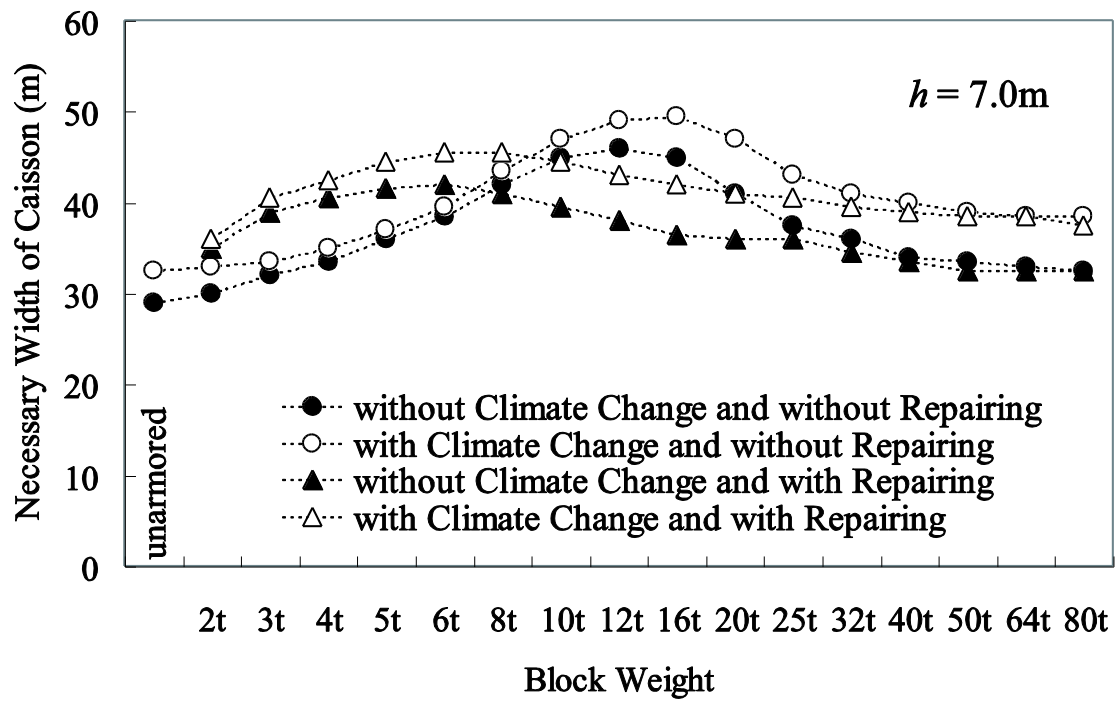
508

509

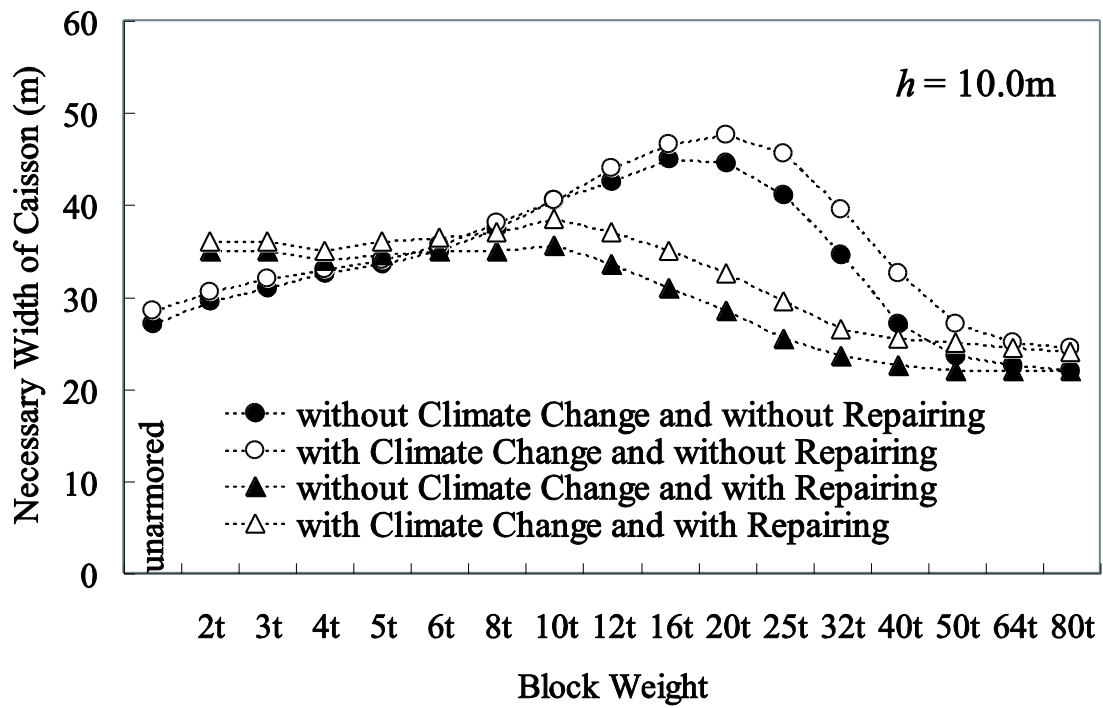510   Figure 9 (a). Necessary caisson width

511

512

513

514

Figure 9 (b). Necessary caisson width

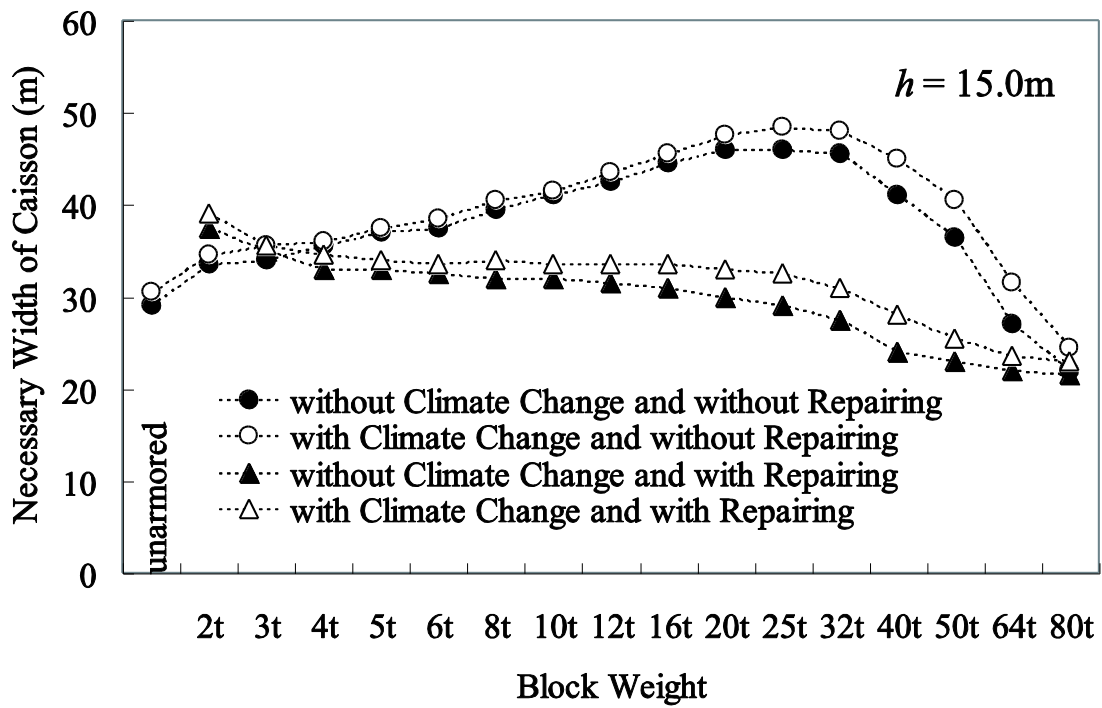515

516

517

518

519

520

521

522

523

524

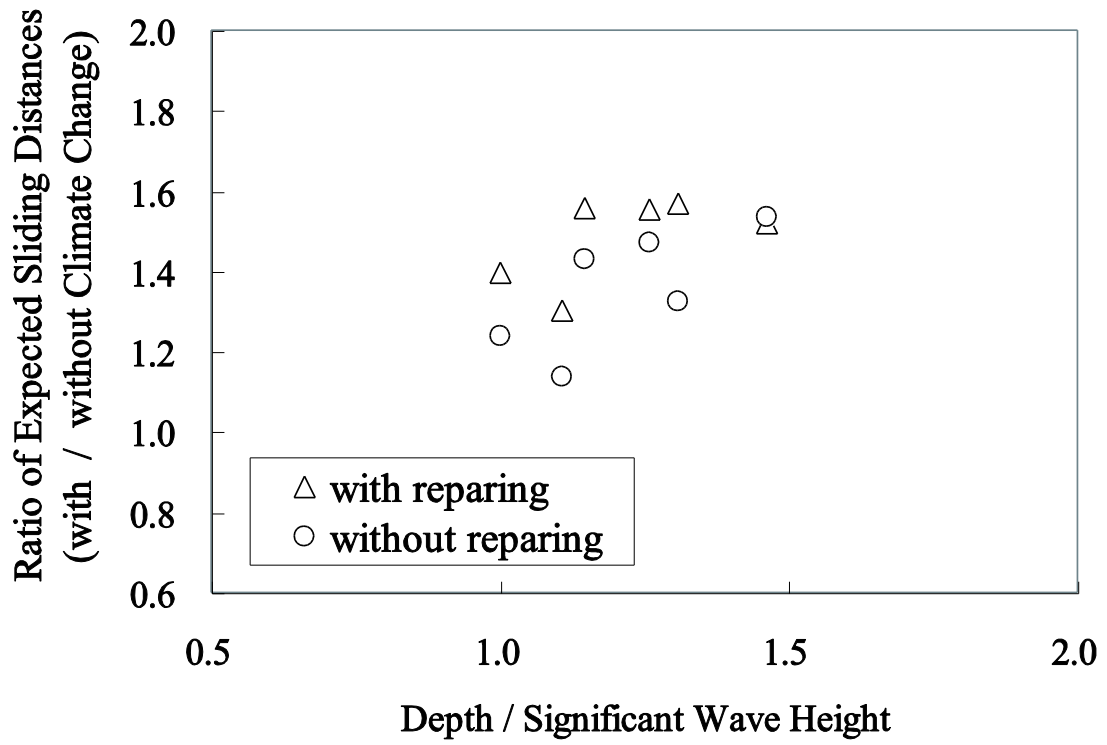525   Figure 9 (c). Necessary caisson width

526

527
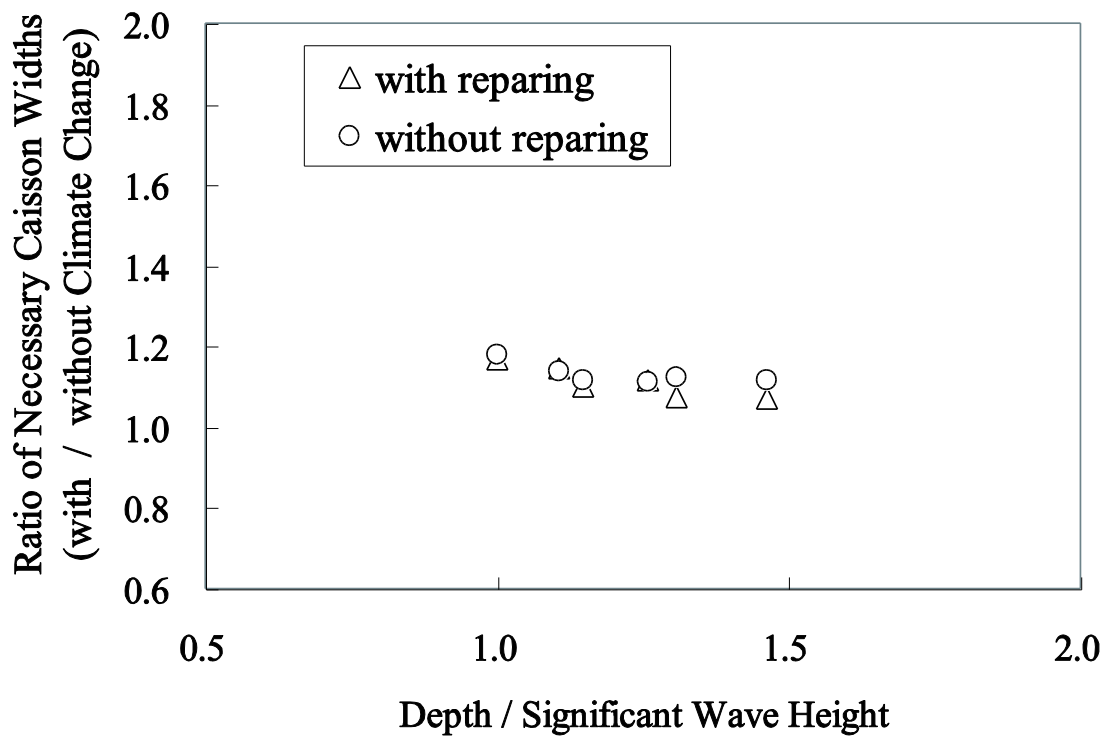
528

529

530

531

532

533   Figure 10 (a). Effects of climate change for expected sliding distance and necessary

534   caisson width

535

536

537

538

539

540   Figure 10 (b). Effects of climate change for expected sliding distance and necessary

541   caisson width

542

543

544

545 Table 1 Calculation conditions

546

547

Item	Value		
Offshore Wave Height Extreme Distribution Function (Summer) in Present Climate	20.07m (λ=0.43) Weibull Distribution with k=1.0, A=4.02, B=7.74		
Offshore Wave Height Extreme Distribution Function (Winter) in Present Climate	10.82m (λ=1.47) Weibull Distribution with k=1.4, A=1.80, B=5.72		
Offshore Wave Height Extreme Distribution Function (Summer) in Future Climate	24.79m (λ=0.53) Weibull Distribution with k=1.0, A=5.25, B=7.58		
Offshore Wave Height Extreme Distribution Function (Winter) in Future Climate	10.84m (λ=0.91) Weibull Distribution with k=1.0, A=1.26, B=6.03		
Water Depth (h)	7m	10m	15m
Width of Caisson when K_r =1.0	16.8m	18.3m	21.3m
Width of Caisson when K_r =0.5	14.3m	16.1m	19.3m
Crown Height of Caisson when K_r =1.0	4.2m	5.2m	6.8m
Crown Height of Caisson when K_r =0.5	3.8m	4.8m	6.4m
Storm Surge Height in Present Climate	2.616m Weibull Distribution with k=1.4, A=0.998, B=-0.248		
Storm Surge Height in Future Climate	3.199m Gumbel Distribution with A=0.646, B=0.358		
Sea Level Rise	0.26m / 100 years		
Duration of a Storm	2 hours		
Service Time	50 years		
Number of Simulation Repetition	10,000 times		
Damage of Concrete Blocks to Be Repaired	5 % of Coverage		

548

549

550

551   Table 2 Allowable sliding distance and excess probability

552

		Allowable Excess Probability of Sliding Distance of a Caisson		
		1.0m	0.3m	0.1m
Importance	1: Low	10%	20%	50%
	2: Ordinary	5%	10%	30%
	3: High	2.5%	5%	15%

553

554

555

556

557