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Geotechnical characteristics of Japanese castle masonry wall and mechanical analysis for its preservation

Caractéristiques géotechniques de la maçonnerie du château Japonais et de son analyse pour conservation

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ABSTRACT
Japanese castle masonry wall constructed from the late sixteenth century to middle of seventeenth century is appreciated as one of the world's finest and outstanding construction culture. This paper initially presents the various geotechnical characteristics of stability in the Osaka Castle masonry wall through the investigation on historical and empirical study and later, the field mechanical analysis by measurement of masonry wall shape and strain over the reconstruction period of the Marugame Castle masonry wall.

RÉSUMÉ
La maçonnerie du château Japonais de la fin du XVIe jusqu'au milieu du XVIIe siècle est appréciée comme l'un des ouvrages les plus raffinés et exceptionnels dans la culture de la construction. Cet article présente tout d'abord les diverses caractéristiques géotechniques de la stabilité du mur de maçonnerie du château d'Osaka à travers une étude historique et empirique. Ensuite, l'analyse mécanique par la mesure de la forme du mur et de ses contraintes durant toute la période de la reconstruction du mur de maçonnerie du château Marugame.

1 INTRODUCTION

The Japanese castle masonry wall (hereafter called wall), constructed from the late sixteenth century to middle of seventeenth century, is appreciated as one of the world's finest and outstanding construction culture. The walls are excellent for the mechanical rational structure and are magnificent and elegant on two dimensional (2D) curved surfaces and on three dimensional (3D) structures. Especially, these walls are characterized by the absence of the use of adhesive agent and are unique in the world for its mortarless construction. Most of these walls have safely withstood more than 350 years since their construction. But present investigations on these walls have shown bulging at various locations. Hence, the investigations are urgently needed on these walls for its geotechnical engineering evaluation on the wall stability and the possible maintenance and management of its preservation.

Based on this view point, this paper presents initially the various geotechnical characteristics of stability in the Osaka Castle wall considering the tallest wall in the Japanese castle structures through the investigation on historical and empirical study and later, the mechanical analysis by field measurements of wall shape and strain over the reconstruction period of the Marugame Castle wall.

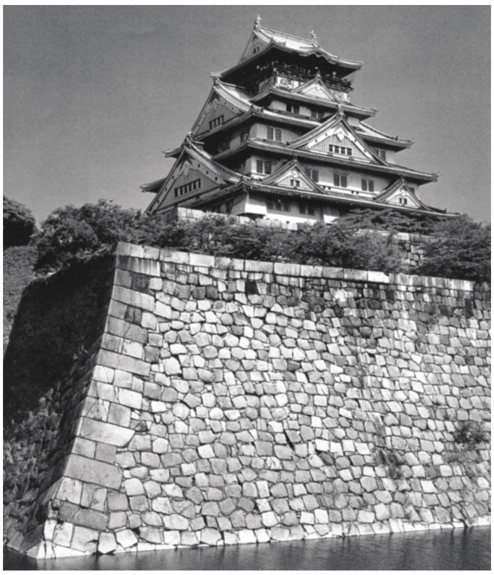
Figure 1. Osaka Castle tower and wall: part of western inner moat.

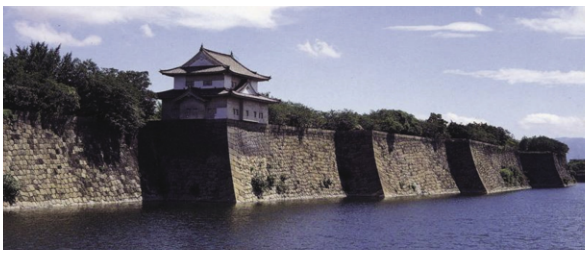
Figure 2. Osaka Castle wall: inner part of southern outer moat.

2 ENGINEERING PROPERTIES OF JAPANESE CASTLE WALL

2.1 *Osaka Castle wall and its structure*

The Osaka Castle wall constructed during 1620-1630, has the tallest wall among castles in Japan with 32m as the maximum height and 12km as the total circumference (Amano et al, 2000). The wall is magnificent and graceful with the execution of the most eminent wall construction technology of Japan. Despite of

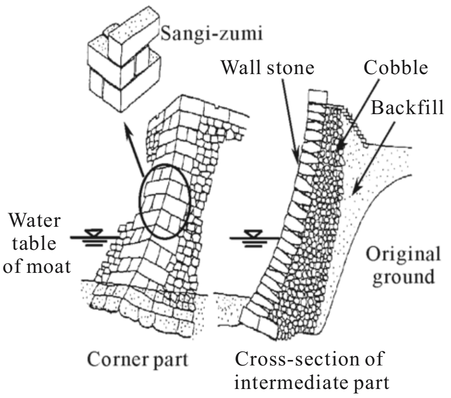

Figure 3. Schematic illustration of wall structure.

past several earthquakes, the Osaka Castle wall has maintained in the stable condition. Figure1 shows the Osaka Castle tower and wall located at the inner part of western inner moat. And Fig. 2 shows the inner part of southern outer moat. The stability of wall is related to many factors like foundation structure, section, shape and the corner zone of wall structure. The principles of stability in the wall are examined for the Osaka Castle wall considering it as the case study.

Figure 3 shows the illustration exhibiting the internal structure of wall at the corner and the intermediate parts. The wall consists of wall stones, cobbles, backfill and the original ground. The wall structure has two roles; one is for the drainage function which prevents wall stones from being greatly affected by the water pressure and the other is to function so as to transmit the earth pressure more uniformly to wall stones. The wall stones are large granite rocks and cobbles comprise of small granite rocks. The upper part of foundation under the Osaka Castle wall is embankment and the lower part is original ground, which has the alternate layer of diluvial clay and gravel. The foundation of the wall consists of the gravel layer exhibiting standard penetration test, N value of 50.

The forms of the Osaka Castle wall are studied on their 2D curved surfaces and their 3D structures. The wall structures are observed to be built with special techniques called "sangi-zumi" at the corner part while the wall stones are being piled one above another against an existing hillside at the intermediate part. The wall structure "sangi-zumi" in which the wall stones are layered one above another in alternate fashion, is a very firm structure and causes the stability effect three dimensionally. The section form with a refined gradient of the wall is found linear to 1/3 from the bottom and then parabolic to the upper part. Figure 4 represents a method for designing a cross sectional shape of wall as adopted in Japanese construction document, "Goto-ke Monjyo" (Morimoto et al, 2000; Nishida et al, 2003). By setting bottom width, b as 21.1m, top width, a as 4.5m and number of division, n as 4, the cross section of the model wall matches perfectly with the existing wall of 32m height.

2.2 *Empirical approach for wall stability evaluation*

The developed frictional resistance τ, occurring between wall stones to resist expansion of the wall surface can be expressed in the equation as $\boldsymbol{\tau=\sigma\tan\phi}$, where σ represents a normal stress acting on wall stones and ϕ represents an angle of shear resistance between their contact zone. The compilation of wall stones are found to be so arranged that their contact zones lie at right angles to the wall ridge. This causes the maximum principal stress to act on the contact zone perpendicularly and is quite rational from the mechanical point of view. As the depth of the wall stone is about three times the side of the front surface, the wall stones are observed to be transmitting the force from the upper to the lower layer smoothly even in the limited bulged case. Hence, the large frictional resistance can be thought to act between the wall stones during earthquakes.

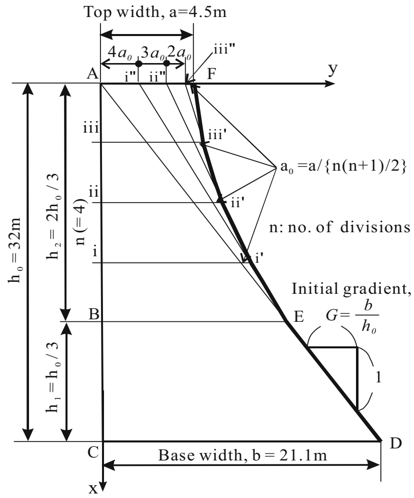

Figure 4. Cross sectional shape of Osaka Castle wall.

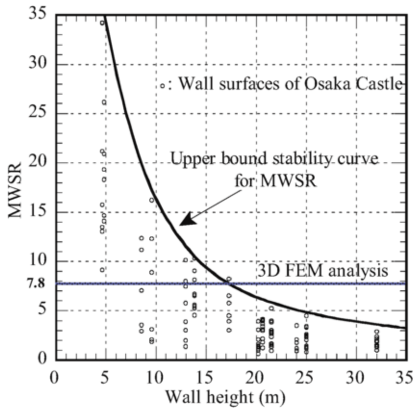

Figure 5. Relation between the wall height and the MWSR at Osaka Castle wall.

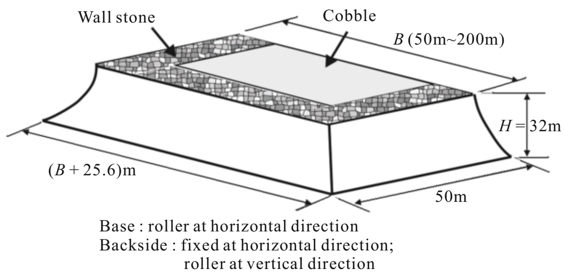

Figure 6. Explanatory model used in 3D FEM analysis.

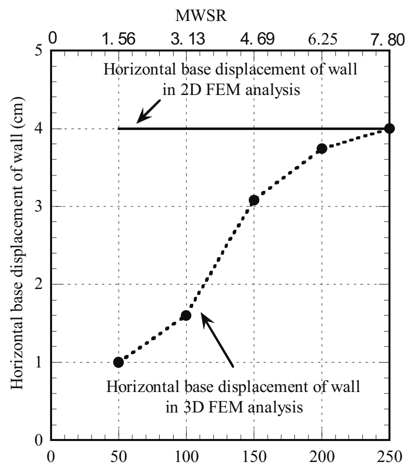

Figure 7. Comparison of horizontal base displacements of walls in 2D and 3D FEM analysis.

The value obtained from dividing the upper length of wall surface by its height is coined by the term “masonry wall structure ratio (hereafter called MWSR)” and this term MWSR is used hereafter to further grasp on the stability of the wall. Figure 5 shows the relation between the wall height and the MWSR at the Osaka Castle wall. The upper bound curve line here reveals that when the wall height reduces to 5m, it exhibits high MWSR value approaching to the mechanical condition with no 3D mechanical effect. On the contrary, it shows the tendency of the upper bound curve line settling to its low value of nearly 3 when the wall height exceeds 24m.

The past failures in walls show that bulgings are observed mostly in the intermediate part of wall. It may prove that the corner part of “sangi-zumi” strongly accounts for the presence of 3D mechanical effect on the wall. The historical technique and know-how that higher the wall height, the smaller the MWSR to be made, is found to be well secured for the wall stability. In order to consider the influence of 3D mechanical effect, 3D FEM analysis was performed with the model as shown in Fig. 6, varying the upper length of wall surface. Figure 7 represents the numerical results of horizontal base displacement at the middle section of wall on varied wall length from 50m to 250m. At the wall length of 50m, the horizontal displacement value is l cm and when the wall length reaches 250m (MWSR= 7.8), it becomes 4cm showing equal to the case of 2D FEM analysis. This shows that 3D corner effect of wall becomes negligible when the MWSR reaches about 7.8. Upper bound stability curve of the MWSR of Osaka Castle wall as shown in Fig.5 also corresponds well as being crooked near its value of 7.8.

Many walls are found to be confronted by the geotechnical engineering method which judges its stability in relation to the maintenance, management and repair technology. As the bulging increases, the wall becomes unstable and results in collapse by the external force of greater impact such as a torrential rain or an earthquake. Hence, the method to grasp the stability of the wall is by “masonry wall bulging index (hereafter called MWBI)” as illustrated in Fig. 8. MWBI is defined as the value obtained from dividing the maximum bulging (represented by cm) against the section form of the wall at the original construction by the height of the wall where the bulging occurs (called the bulging height and represented by m). Figure 9 shows the relation between this bulging height and the MWBI based on the investigation cases of bulgings for various Japanese castle walls. Among them, five were the collapse cases by the torrential rain and the earthquake; from the relations obtained, upper bound MWBI value was determined to evaluate for the severe conditions before the collapse of wall. It was nearly 6 before the collapse and for higher values, the walls were found to be in the unstable condition due to increased bulgings. Thus, it is inferred that the wall exhibiting MWBI greater than 6 has high potential for a collapse by the external force of a greater impact.

2.3 *3D mechanical effect of bi-curvilinear wall surface*

Figure 10 is a 3D FEM analysis model created for the wall length of 77m with top surface straight line and incorporating “hiranosuki” (Amano et al, 2000) bi-curvilinear surface at the Osaka Castle wall. The normal stresses obtained from 3D FEM analysis for “hiranosuki” value, h of 0m and 5m are summarized for the stone element at A position of wall (10.6m height from base as shown in half model) in Table1.The normal stresses in the vertical and horizontal directions, σ_y and σ_z are found to be successively increasing in the compressive sides from the outer 1st element towards the direction of inner 5th element of a wall stone in the “hiranosuki” analysis cases and further the innermost element of wall stones are subjected to comparatively larger compressive stresses against the case with the increased “hiranosuki” value of 5m . This shows that A position of the wall surface is found to be subjected primarily to compression forces on both vertical and horizontal directions, which should be due to the action of arching effect on wall structure. From this analysis, it can be concluded that the appropriate consideration of “hiranosuki” in the wall enhances the stability of the wall.

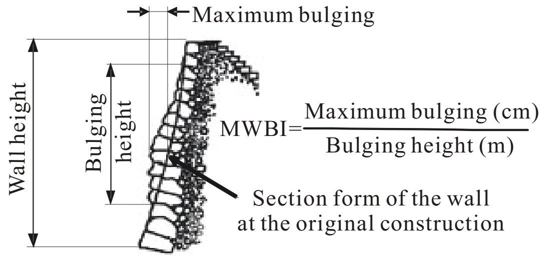

Figure 8. Illustration of MWBI.

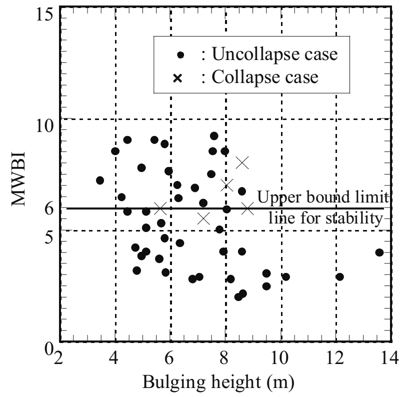

Figure 9. Relation between the bulging height and the MWBI for various walls.

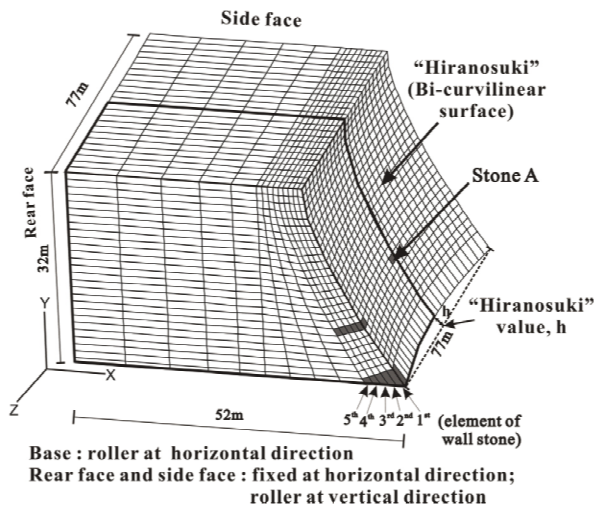

Figure 10. 3D FEM analysis model incorporating “hiranosuki”.

Table 1. Comparision of stresses considering “hiranosuki” (Stone A).

(+): Compression (-): Tension

h	Stresses	Finite element number of stone starting from outside surface				
	(kN/m^2)	1st	2nd	3rd	4th	5th
0 m	σ_x	-104	16	163	355	532
	σ_y	-186	465	1071	1633	2150
	σ_z	74	139	195	242	282
5 m	σ_x	-93	29	187	379	600
	σ_y	-95	619	1276	1875	2417
	σ_z	13	108	193	270	345

Elastic modulus, $E = 4\times10^6$ kN/m^2; poisson's ratio, ν =0.15

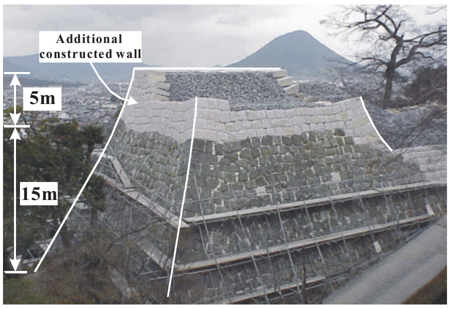

Figure 11. Marugame Castle wall during the reconstruction stage of wall height from 15m to 20m

3 FIELD MEASUREMENT AND ITS MECHANICAL ANALYSIS

Based on the exact field measurements on the wall surface, the geotechnical engineering evaluation in the Marugame Castle wall situated at Sikoku of Japan was carried out during its reconstruction period. Figure 11 shows the state of Marugame Castle wall during the reconstruction of its wall up to extreme height of 20m.

The executed work schedule for additional wall construction from 15 m to 20 m is shown in Fig.12. The mechanical measurements of strains were carried out attaching three directional 45° rectangular rosette gauges to the wall stone surfaces, temperature from sensors and the gap quantity between wall stones from displacement transducer set at the wall stone surfaces. The measurement was performed throughout the construction period at wall stone positions of height 6.5m and at 15m from the base for the corner and the intermediate parts of wall respectively. Then the stress release technique was accomplished by over coring of diameter 10cm to depth 10cm for investigated wall stone surfaces at corner and intermediate parts. The original stresses acting at the 15m height of wall were restored from the stress variation after the over coring operation.

The strains ε_1, along vertical direction, ε_2, along horizontal direction and ε_3, along 45° inclined direction during the construction period after applying correction for temperature are shown in Fig. 13. And vertical displacement variations after the temperature correction between wall stones during the additional construction of wall from 15m to 20m were found in the range of 0.3 mm to 1.4 mm. Figure14 represents the displacement variation for case at height 6.5m corner wall stone and is accompanied by a decrease in its gap. This shows that the compressive force is acting in longitudinal direction.

The strains at 15m stage, during its construction from 15m to 20m stage and at 20m stage are tabulated in Table 2. Here, the resulted strains are compressive and especially the occurrence of compressive strain in horizontal direction, ε_2 accounts for 3D mechanical effect of the wall. Further, the strains ε_1, ε_2 and ε_3 during the stage of additional construction for wall stone at 6.5m height were in the range of 23μ to 51μ and the maximum principal strains at the final stage being all compressive substantiate for the stability of the wall.

Next, the principal stress and shear stress distributions were calculated from the strains resulted at wall stones of corner part and intermediate part in Table 2 and were compared in Table 3. For the wall stone at 6.5m height corner position, the maximum principal stress was obtained as 1329 kN/m^2 in compression and minimum principal stress as 182 kN/m^2 which also being in compression demonstrates the presence of 3D mechanical effect of wall structure. This associates the development of compressive forces in both direction and can be concluded that the major stress distribution on the wall is being shared by the corner part relative to that by other parts.

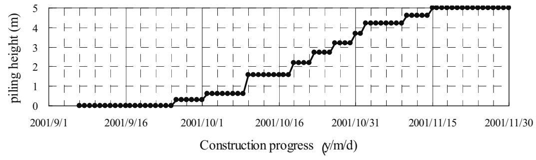

Figure 12. Executed work schedule for reconstructed wall.

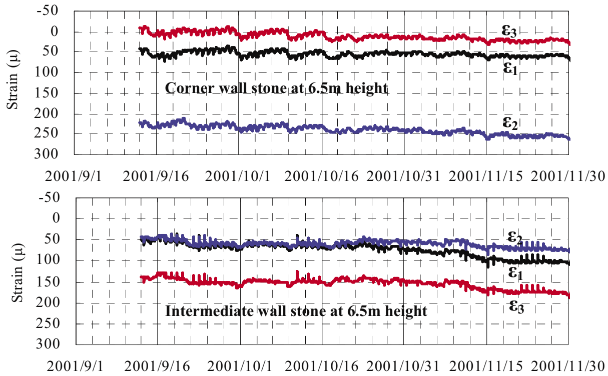

Figure 13. Strains at corner and intermediate part (+:comp; -:tension).

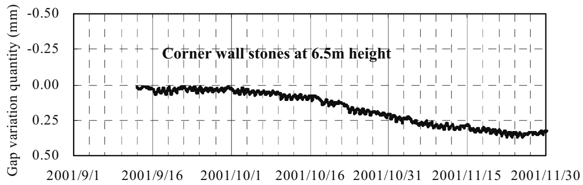

Figure 14. Vertical displacement variation between corner wall stones (+:shrinkage; -:elongation).

Table 2. Strains of wall stones.

(+:comp; -:tension)

Meaurement locations	strains (μ)	15m	15m ~ 20m	20m
15m height (corner)	ε_1	-	132	132
	ε_2	-	14	14
	ε_3	-	95	95
6.5m height (corner)	ε_1	42	23	65
	ε_2	221	35	256
	ε_3	-10	36	26
6.5m height (intermediate)	ε_1	50	51	101
	ε_2	43	29	72
	ε_3	138	38	176

Table 3. Principal stresses of wall stones.

(+:comp; -:tension)

Meaurement locations	σ_{max} (kN/m^2)	σ_{min} (kN/m^2)	τ_{max} (kN/m^2)
15m height (corner)	563	125	219
6.5m height (corner)	1329	182	574
6.5mheight (intermediate)	722	92	315

Elastic modulus, E = 4×10^{6}kN/m^2; poisson's ratio, ν =0.15

4 CONCLUSIONS

Summarizing the results lead to the following conclusions:

1. The features of wall shapes and structures are determined based on the historical and empirical approach of Osaka Castle wall.
2. The stability assessment method and principles of wall stability are revealed based on MWSR and MWBI.
3. Presence of “sangi-zumi” and introduction of “hiranosuki” to the wall enhances the 3D stability of the wall.
4. The wall stability and principles of preservation are considered from the application of the mechanical measurement results of the Marugame Castle wall.

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