# DEGRADATION AND MASS LOSS OF JAPANESE CEDAR CYLINDRICAL PILES BURIED FOR 10 YEARS WITH THEIR HEADS AT THE GROUND SURFACE

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Timber piles for ground improvement have many potential applications, and increasing carbon storage by expanding their usage is expected to contribute to net-zero greenhouse gas emissions by 2050. For this contribution to be reported by the Government of Japan, the rate of mass loss of underground wood must be estimated quantitatively; however, the rate of mass loss is currently unknown. In this paper, a study was performed of Japanese cedar cylindrical piles that were excavated after being buried with their heads at the ground surface for about 10 years in the Inashiki plateau, Japan. The rate of mass loss was analyzed, assuming that no wood decay occurred at depths below the lower limit of the groundwater level. The part of the piles in the range of groundwater fluctuation did not have recognizable mass loss. However, at depths above the upper limit of the groundwater level, the half-life of the mass loss of the parts of the piles where the outer peripheral shape remained was about 50 years, and that of the parts with cross-sectional loss was less than about 10 years.

***Key Words:*** *wood utilization, carbon storage effect, underground utilized wood, mass loss, timber pile*

## 1. INTRODUCTION

In October 2020, the Japanese government declared its target to achieve zero greenhouse gas emissions by 2050. However, some emissions that cannot be fully reduced will remain even in 2050 and must be offset by various carbon removal activities to achieve net zero emissions. One technically feasible and effective method is carbon storage by expanding the use of wood products, whereby increased carbon storage in a given year is treated as carbon removed from the atmosphere in that year.

Wood utilization in the civil engineering sector has many potential applications. Especially, the carbon storage effect of using wood in the ground is estimated to be much greater than that of other uses[1)]. Established countermeasures against liquefiable ground and cohesive soft clay ground include driving logs below the groundwater level to densify the ground[2), 3)] and using wooden friction piles[4)-6), etc.] and raft foundations[7)] to prevent differential settlement. In Japan, loose sandy liquefiable ground was formed near the coastline when the sea advanced in the Jomon era, whereas clayey cohesive ground was formed farther away from the coastline. Today, large populations and much infrastructure are concentrated in these areas, and thus there is a pressing need for ground improvement, for which the potential for timber use is high.

The Japanese government submits a national greenhouse gas inventory report to the United Nations Framework Convention on Climate Change Secretariat every year. However, the use of roundwood ("logs" in this paper) is not currently included in the calculation of $CO_2$ removal and emission by harvested wood products (HWP). To report the carbon storage effect of underground timber use in civil engineering works in the inventory report, it is necessary to show "transparent and verifiable" data on how long and what amount of carbon is stored in timber used underground.

There have been many reports of tests conducted by excavating timber piles used for construction foundations[8)-16) etc.]. However, most reports describe the mechanical properties of timber piles as supporting piles from an engineering perspective, and there is little information on chronological and quantitative data that can be used to evaluate carbon storage capacity or half-life period of mass loss, such as how the density of underground timber piles changes over time.

In this paper, we quantitatively evaluated the mass loss rate of cylindrical timber piles made of Japanese cedar that were buried in the ground in the Inashiki Plateau with their heads at the ground surface for 10 years, and then excavated.

## 2. BURING AND EXCAVATION OF THE CYLINDRICAL PILES

In October 2021, we excavated three Japanese cedar (*Cryptomeria japonica*) cylindrical piles that were processed from logs into cylindrical columns and had been buried on the premises of the Forestry and Forest Products Research Institute (FFPRI) in Tsukuba, Ibaraki Prefecture with their heads at the ground surface since December 2011 for approximately 10 years.

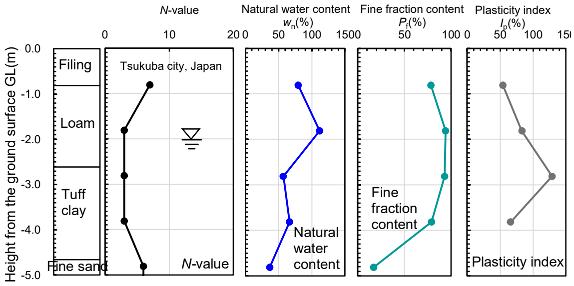

**Fig. 1** Boring log and physical properties of soil at the excavation site of the cylindrical piles.

The Inashiki Plateau is part of a diluvial plateau called the Hitachi Plateau in the southern part of Ibaraki Prefecture and is 25 m to 50 m above sea level. The stratigraphic sequence of the Inashiki Plateau consists of the new Kanto Loam Formation as the upper layer and the Joso Formation as the lower layer. **Figure 1** shows the boring log and physical properties of the soil obtained from the boring conducted at the time of excavation. The groundwater level one day after the boring at the time of excavation was ground level (GL) −2.0 m. According to the borehole investigation conducted in January 2010, the groundwater level was at GL −2.6 m.

Therefore, in this study, we assumed that GL −2.0 m was the upper limit of the groundwater level, the range between GL −2.0 m and −2.6 m was that of groundwater fluctuation, and GL −2.6 m was the lower limit of the groundwater level. Considering that the excavation was conducted in October when rainfall was relatively high and the drilling in 2010 was conducted in January when rainfall was low, the assumed groundwater levels represent the approximate fluctuation of the groundwater level at the site. Because there is a regulating reservoir on the premises of FFPRI and there are rice paddy fields in the surrounding area, the bottom ends of the cylindrical piles buried down to a depth of about GL −4.2 m were assumed to be below the lower limit of the groundwater level, although accurate fluctuation of the groundwater level was not measured.

The N-value at depths above GL −5.0 m was 3 to 6, showing that the soil was hard for clay soil ground. The values of the ratio of natural water content, fine fraction content, and plasticity index were all high, assuming that the soil permeability was low (**Fig. 1**).

**Photo 1** shows the excavation of the cylindrical piles. A steel pipe with an inner diameter of approximately 300 mm was attached to construction equipment with a leader. The steel pipe was rotated and driven slowly into the ground so that the cylindrical

**Photo 1** Excavation of a cylindrical pile.

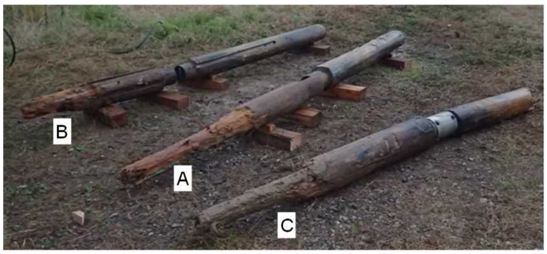

**Photo 2** Excavated cylindrical piles.

pile was inserted into the pipe, and when the pile was disconnected from the surrounding ground, it was pulled up using a fabric rope.

**Photo 2** shows the three cylindrical piles excavated. The upper left pile is referred to as B, the center as A, and the lower right as C.

Underground foundation piles, which are fixed to superstructures and reach the underground supporting layer, are subject to bending and shear stresses when external forces, such as earthquakes, are applied. Because long piles are difficult to transport and handle during pile-driving, it becomes necessary to joint short piles longitudinally during pile-driving. Thus, the development of longitudinal joints that could bear bending and shear stresses was a problem at the time of the initial experiment.

Each cylindrical pile excavated consisted of two cylindrical timber elements (upper element and lower element), each 2.1 m long and 0.2 m in diameter, jointed longitudinally using various types of metal joints. The photo of cylindrical pile C shows the pile before the metal joint was removed. Some of the cylindrical piles had strain gauges attached to them to measure the stresses applied to the piles during pile-driving. Cylindrical pile B had grooves carved on the surface, through which lead wires were connected to sensors and the main aboveground equipment. The grooves were covered with a long, thin plastic cover while the pile was buried underground.

**Figure 2** shows the position of the cylindrical piles when they were buried in terms of their depth from the ground surface. Photographs taken at the time of burying show that the heads of the piles were at the same level as the ground surface and that the pile heads were visible. Thereafter, the pile heads were covered by a blue sheet for a period, and at the time of excavation, the pile heads were not visible at the ground surface because they were covered with soil. The lower elements of piles A and B had original lengths of 2.1 m with the bottom ends of the piles at GL −4.2 m. However, the length of the lower element of pile C was about 1.4 m. The lowest part of 0.7 m long of the original element had been lost, possibly during pile-driving when it was crushed by rocks or other obstacles in the ground when the pile was driven into the soil.

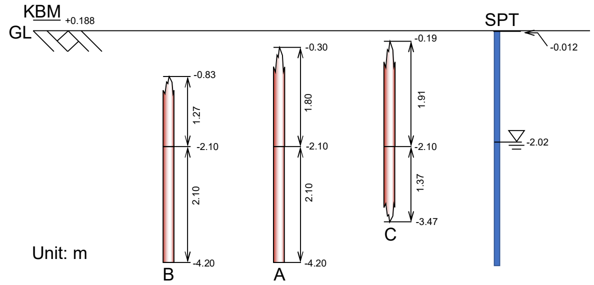

**Fig. 2** Location map of cylindrical piles in the depth direction.

Although initially the upper element was driven into the ground until the head was at the same level as the height of the ground surface, the upper elements of the piles after excavation were approximately 1.3 m to 1.9 m long, and 0.2 m to 0.8 m of the top sections of the upper elements were entirely lost. These losses were not necessarily caused solely by decay, and a portion might have been destroyed by the heavy machinery used to excavate the decayed piles. The part of upper elements where the outer surface of cylindrical shape remained intact and cross-sectional loss did not occur was 0.6 m to 1.1 m long. The part where cross-sectional loss occurred was 1 m to 1.5 m long, from the top of the upper elements of the cylindrical piles.

The upper and lower elements of piles A and B did not originate from the same trees, judging from the pattern of the annual rings; whereas the two elements of pile C may have come from the same tree, although this was not confirmed.

## 3. EVALUATION PROCEDURES AND METHODS

### (1) Overview of the evaluation

From the excavated cylindrical samples, the ratio of remaining mass was determined for each depth, and this was used to determine the half-life period of mass loss. The initial mass must be known in order to determine the ratio of remaining mass, but this information was not available. Therefore, based on the results of past investigations of wood buried underground, it is assumed that wood retains its soundness at depths below a certain groundwater table[11), 12)]. Therefore, we first investigated the decay of the cylindrical piles in the longitudinal (L) direction and specified the depth at which the piles are assumed to be sound, by comparing the tested values with the general values of the wood species. The mass at this depth was taken as the initial mass. Next, the ratio of remaining mass in the longitudinal (L) direction was evaluated based on the cut cylindrical piles, and the ratio of remaining mass in the radial (R) direction was evaluated from small block specimens.

The following procedures were used to evaluate the wood samples:

(a) Cylindrical piles were washed with water at the excavation site, the degree of degradation was visually evaluated, and a Pilodyn penetration test was conducted.

(b) For ease of transport, each pile was cut cross-sectionally into short columns of approximately 500 mm in length. In addition, disks approximately 200 mm thick were cut from three depths: that below the lower limit of the groundwater level, that between the fluctuating groundwater level, and that above the upper limit of the groundwater level. The 200 mm thick disks were transported to Laboratory F, while the other cylindrical piles were transported to Laboratory T.

(c) At laboratory T, the cylindrical piles were immersed in water until they stopped floating, so that the water content of the piles exceeded the fiber saturation point, thereby removing the effect of water content on the compression test. Subsequently, compression tests parallel to the grain and bulk density measurements were conducted.

(d) At laboratory F, small block specimens were cut from a disk of approximately 200 mm to evaluate the ratio of remaining mass in the R direction, and accurate tests were conducted. Compression tests were also conducted at laboratory F. The results of the compression tests of small block specimens did not affect the conclusions of this paper and are omitted here.

Each test was evaluated as follows.

### (2) Assessment of the visual degree of decay (excavation site)

To determine the visual degree of decay of the cylindrical piles, three assessors, identified by their initials (N, T, and K), observed the surface of the sides of the piles at depth intervals of 0.1 m from the top to the bottom and at four points at intervals of 90° around the perimeter at each depth. For visual evaluation, a 4 cm × 4 cm square frame was drawn on the surface of the log at each evaluation position, and the conditions within the frame were visually observed and evaluated according to the following six categories, referring to JIS K1571.

0: Sound
1: Partial slight decay or termite damage
2: Slight decay or termite damage over the entire surface
3: Partial severe decay in addition to condition 2
4: Severe decay or termite damage over the entire surface
5: Collapse due to decay or termite damage

### (3) Pilodyn penetration tests (at the excavation site)

For the purpose of providing a somewhat quantitative assessment of the visual degree of decay, Pilodyn penetration tests were conducted at the surface of piles A and C at the same positions as the assessment of the visual degree of decay. The pin of the Pilodyn tester penetrated in the R direction from surface of the piles. The test could not be conducted for pile B because the Pilodyn tester was broken. In the places where there was cross-sectional loss in the upper elements of the piles, the Pilodyn tests were conducted on the surface of remaining portion, and the radial lengths of the lost parts were added to the measured values of the Pilodyn penetration. Consequently, the estimated results of the penetration tests exceeded the maximum measurable Pilodyn penetration of 40 mm in these cases.

### (4) Compression tests parallel to the grain (in laboratory T)

Short columnar specimens with a maximum length of about 400 mm (twice the diameter) were cut from the excavated piles and compression tests parallel to the grain were conducted in accordance with JIS Z 2101.

Because disks were also cut from the three cylindrical piles for other tests, the short columnar specimens did not cover the entire length of cylindrical piles. Some of the short columnar specimens were less than 400 mm long, with the shortest one being 165 mm long.

There were parts with cross-sectional loss in the upper elements of the cylindrical piles. Estimating compression strengths parallel to the grain based on the remaining cross-sectional areas in these parts would result in an overestimation of the strength per unit area despite the severe degradation. Therefore, the original cross-sectional areas of the cylindrical piles before decay were used for estimating compression strength in these parts. For the original cross-sectional areas, we used the cross-sectional areas of the uppermost position in the range below the upper limit of the groundwater level of the upper elements of the piles. As described below, in the visual grade of decay and Pilodyn penetration tests, the cylindrical piles were completely sound at depths below the upper limit of the groundwater level.

For pile B, which as mentioned above had grooves, the cross-sectional areas of the short columnar specimens were calculated as follows: the groove sizes were measured with calipers; the volumes of the groove spaces were calculated; the groove volumes were extracted from the short columnar specimen volume, which was calculated assuming a cylindrical shape; and finally the extracted volumes were divided by the short columnar specimen lengths. The diameter of the short columnar specimens was determined by measuring the circumference at the three points in the L direction with a pi gauge and averaging them, and the cross-sectional area was obtained from the average diameter assuming a perfect circle. The height was determined by measuring the height at three points with a height gauge and averaging them. Cross-cutting was performed with a circular saw in the laboratory, so that both cross-sectional surfaces of the short columnar specimens were smooth and parallel.

### (5) Results of bulk density measurements (laboratory T)

The short columnar specimens were cut further to a maximum length of approximately 200 mm, and their bulk density was measured. The volume was measured in the same way as in the compression test parallel to the grain. Dimensional measurements were performed on specimens cut after the compression test was performed. As in the compression test, some of the specimens were short, with the shortest specimen being 81 mm in length, and similarly, if the bulk density of the part with cross-sectional loss were estimated based on the volume of the remaining part, the bulk density would be overestimated. Therefore, to estimate bulk density, the volume of specimens with cross-sectional loss was determined by multiplying the length of the specimen by the cross-sectional area of the short columnar specimen at the shallowest point below the upper limit of the groundwater level among specimens for which the bulk density could be measured. The oven-dry weight was measured by thoroughly drying the specimens in the oven after the compression test was conducted.

### (6) Ratio of remaining mass in parts with cross-sectional loss (laboratory F)

The parts of cylindrical piles with cross-sectional loss were cross-cut into disks 100 mm –200 mm high in the L direction. For each disk, a compression test was conducted, and then the oven-dry weight was measured.

The bulk density of the bottom ends of the lower elements of the cylindrical piles (below the lower limit of the groundwater level) was estimated by calculating the weighted average of the bulk density of the small block specimens taken in the R direction from surface to pith (as shown later). The ratio of the area of the 20 mm wide ring-shaped part that contained each specimen to the total cross-sectional area was used, assuming that the bulk density was uniform around the cross-section and the bulk density of the small block specimen was representative of the ring-shaped part. The value of the bulk density of the bottom ends of the lower elements estimated in this way was 298 kg/m$^3$. This value was similar to the bulk density of the short columnar specimens shown in **Fig. 7** and was used as the value for the initial bulk density before the cylindrical piles were buried. Assuming that the initial diameter of the part with the cross-sectional loss of the cylindrical piles was 200 mm, the ratio of the remaining mass of each disk-shaped specimen was estimated by using the estimated initial bulk density and the bulk density of the remaining mass.

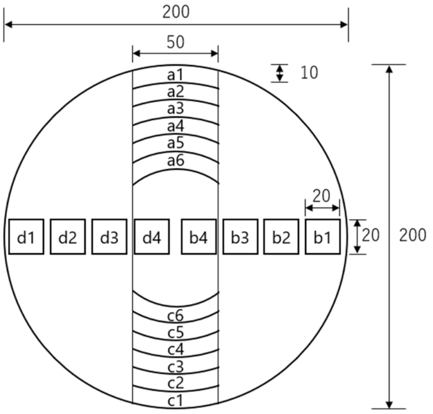

**Fig. 3** Specimen sampling positions in the disks (Units: mm).

### (7) Bulk density of small block specimens (laboratory F)

Disks were obtained from the following three depth positions of the piles: near the bottom end of the lower element (depth position no. 1); near the top end of the lower element, just below the joint (depth position no. 2); and immediately below the part with cross-sectional loss of the upper element where the shape of the outer circumference was retained (depth position no. 3).

The depths of these disks from the ground surface were about GL −4.2 m (about GL −3.5 m for pile C) for depth position no. 1; GL −2.3 m for depth position no. 2; and GL −1.0 m to −1.5 m for depth position no. 3. These depths were below the lower limit of the groundwater level for position no. 1; between the lower and upper limit of the groundwater level for position no. 2; and above the upper limit of the groundwater level for position no. 3.

**Figure 3** shows the positions where specimens were collected from the disks. The specimens were taken from parts of the disks that were free of knots and other defects, and free of any obvious visible compression wood $^{\mathrm{Note\ 1)}}$. Specimens for compression tests (dimensions: 20 mm × 20 mm × 40 mm in the L direction) were cut starting from a position as close

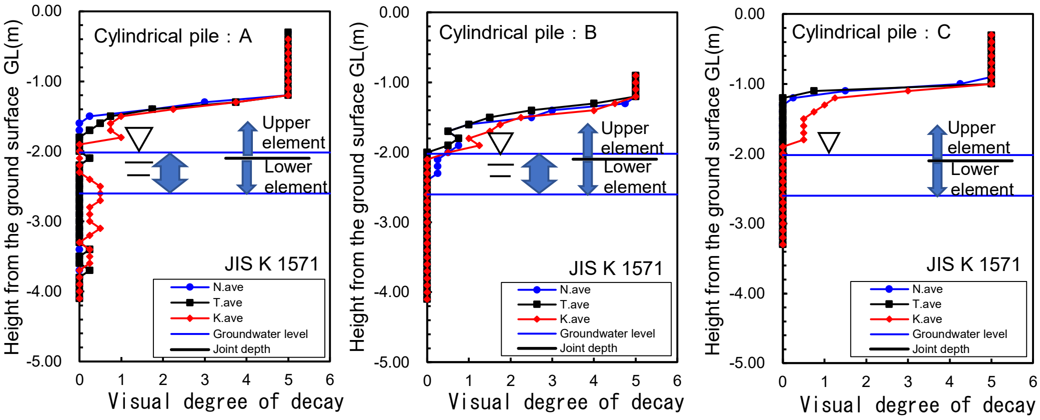

**Fig. 4** Assessment of the visual degree of decay of cylindrical piles.

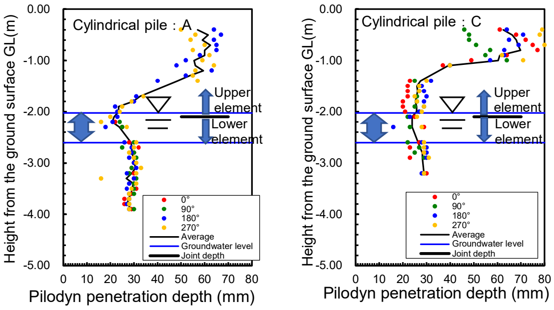

**Fig. 5** Results of the Pilodyn penetration test of piles A and C.

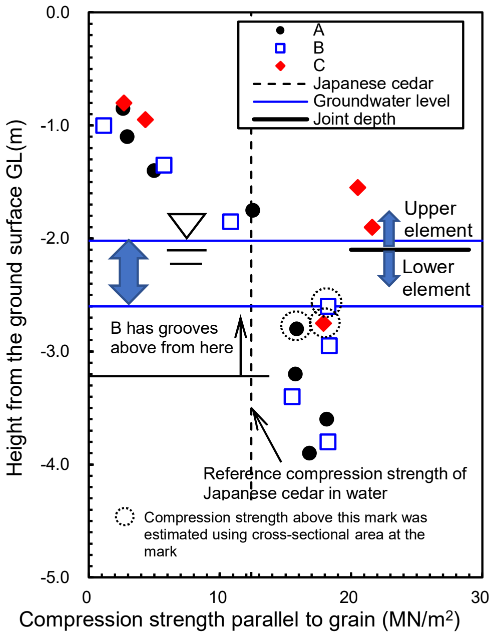

**Fig. 6** Compression test parallel to the grain of the cylindrical piles.

to the outer circumference as possible toward the pith using a saw (blocks b and d). Specimens for measuring bulk density (blocks a and c) were taken by splitting specimens 10 mm thick in the R direction and with an average volume of approximately 14,000 mm$^3$ with a curved chisel from approximately the same plane as the specimens for the compression tests.

## 4. EVALUATION OF MASS LOSS IN THE CYLINDRICAL PILES

### (1) Visual assessment of the degree of decay

**Figure 4** shows the distribution of the decay assessment results along the depth. Each value is the average of the assessment of the four points around the perimeter at each depth. Visual decay below the upper limit of the groundwater level was almost zero, and no decay was observed visually in this part, although there was slight variation among assessors.

The decay was more severe at depths above the upper limit of the groundwater level. In the upper elements of the cylindrical piles, there were parts where the visual degree of decay was judged as 5 and large portions in the cross section were lost. The parts judged as “sound” were below around GL −1.0 m for pile C, GL −2.0 m for pile B, and GL −1.5 m for pile A. Thus, there were differences in the depth of the sound parts among the piles, and pile A was intermediate between the other two piles.

### (2) Results of the Pilodyn penetration tests

**Figure 5** shows the distribution of the results of the Pilodyn penetration test along the depth. Penetration values of about 30 mm or less, which is sound wood, were observed at depths below the upper limit of the groundwater level for pile A, and at depths below GL −1.0 m, which was above the upper limit of the groundwater level, for pile C. These results are consistent with the visual grade of decay.

### (3) Results of the compression tests parallel to the grain

**Figure 6** shows the distribution of the compression strength parallel to the grain along the depth. The compression strength of water-logged Japanese cedar

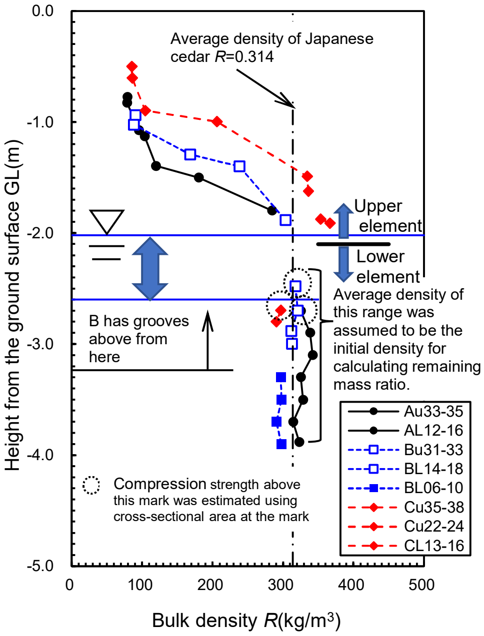

**Fig. 7** Bulk density of the cylindrical piles.

as specified in Article 5 of Ministry of Construction Notification No. 1452 in FY 2000 is shown for comparison. In piles A and B, for the part below the upper limit of the groundwater level, although there was some fluctuation of the value within the same cylindrical pile, the compression strength was stable in the range of 15.5 MN/m$^2$ to 18.6 MN/m$^2$ , which was larger than the standard compression strength of Japanese cedar, and thus this part had not decayed. In contrast, for the part above the upper limit of the groundwater level, the compression strength decreased toward the ground surface. For pile C, however, the compression strength of the part around GL −1.5 m to GL −2.0 m, which was above the upper limit of the groundwater level, was higher than that below. This result is consistent with the assessment of visual grade of decay and of the Pilodyn penetration test. The large values in the shallower part may be caused by differences in the material and because the upper and lower elements of the pile did not originate from the same tree.

### (4) Results of bulk density measurements

**Figure 7** shows the distribution of bulk density along the depth. The average bulk density of Japanese cedar[17)] is also shown in the figure. The bulk densities at depths below the upper limit of the groundwater level were similar to the average value for Japanese cedar, did not change in the depth direction, converged to a constant value, and tended to be constant. This result was consistent with the assessment of the visual grade of decay, Pilodyn penetration tests, and compression tests, and thus we concluded that decay did not progress at depths below the upper limit of the groundwater level.

In contrast, above the upper limit of the groundwater level, the bulk density decreased toward the ground surface. This tendency was also observed in the visual grade of decay, Pilodyn penetration tests, and the compression tests.

In an environment where a timber pile is above the upper limit of the groundwater level, decay is considered to be influenced by the degree of adhesion between the soil and the surface of the pile. Even if the soil is fine-grained and has low permeability, and air penetration is low, like the soil at the site in this study, air and fungi can still easily penetrate the gap between the soil and the wood surface if the adhesion between the wood surface and the ground is low. For an ordinary tapered timber pile, the head of the pile has a larger diameter than the bottom end, and it is assumed that the degree of adhesion between the soil and the surface of the log pile increases as the pile is driven into the ground. However, for the cylindrical piles in this study, the adhesion between the soil and the wood surface may have been weak. This difference in adhesion may explain the difference in the degree of decay among cylindrical piles around GL −1.0 m to GL −1.8 m. In general, tapered timber piles are used for countermeasures against liquefaction or for improvement of cohesive soft clay ground, and the heads of the piles are often driven into the ground to depths below the upper limit of the groundwater level, different from this study.

**Figure 7** shows that the bulk density tended to increase with the depth from around GL −0.8 m to GL −1.4 m. This indicated that the decay did not occur uniformly over the entire area above the upper limit of the groundwater level and that the progress of decay might have been slower below a certain depth.

### (5) Half-life period of mass loss

Although the initial bulk density of the cylindrical piles before burying was unknown, decay did not occur below the upper limit of the groundwater level. Therefore, the average bulk density below the upper limit of the groundwater level was taken as equivalent to the initial value of the bulk density for each cylindrical pile. Consequently, the difference between the measured bulk density and the average bulk density below the upper limit of the groundwater level was the mass loss, and the ratio of the remaining mass was calculated as the ratio of the measured bulk density at each depth to the average bulk density below the upper limit of the groundwater level.

**Figure 8** shows the distribution of the ratio of the remaining mass along the depth. In determining the initial bulk density, the ratio of remaining mass below the upper limit of ground water level was assumed to be almost 100%. The highest values and

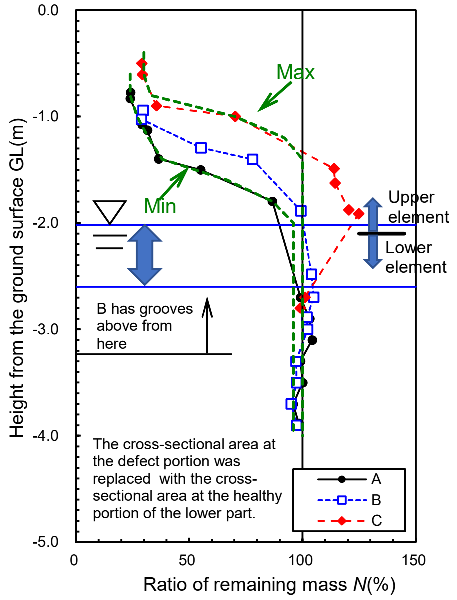

**Fig. 8** Ratio of remaining mass of cylindrical piles.

lowest values of the three cylindrical piles are indicated by the green dashed lines, with the maximum value set to 100%. The lowest value at depths below the upper limit of the groundwater level was 96% due to statistical dispersion and this was a conservative value without overestimation.

Mass loss due to decay or other causes of physicochemical and biological cases can generally be often expressed by the first-order decay function shown in Equation (1).

$$M_t = M_0 \cdot \exp(-k \cdot t) \qquad (1)$$

where $M_t$: Mass after $t$ years (g)
$M_0$: Initial mass (g)
$k$: Decomposition constant (1/years)
$t$: Years elapsed (years)

If the half-life period is $HL$ (y), $M_t / M_0 = 1/2$ From this, $k$ is derived by Equation (2).

$$k = \ln(2) / HL \qquad (2)$$

Substituting Equation (2) into Equation (1), we obtain Equation (3) for $M_t$ using $HL$.

$$M_t = M_0 \cdot 2^{(-t/HL)} \qquad (3)$$

The half-life period of mass loss at each depth was obtained from the distribution of the maximum and minimum ratio of remaining mass along the depth (**Fig. 8**), where $M_0$ = 100 and $M_t$ is expressed as a percentage.

**Table 1** shows the half-life period of mass loss. The maximum and minimum values shown here are only those for the three cylindrical piles excavated in this study.

**Table 1** Half-life period of mass loss calculated from the depth distribution of the ratio of remaining mass in cylindrical piles.

| Height from GL (m) | Remaining mass ratio Min. (%) | Remaining mass ratio Max. (%) | Half-life period Min. y | Half-life period Max. y |
|---|---|---|---|---|
| -0.6 | 24 | 30 | 4.8 | 5.7 |
| -0.8 | 24 | 33 | 4.8 | 6.1 |
| -1.0 | 27 | 70 | 5.2 | 19 |
| -1.2 | 32 | 92 | 6.0 | 82 |
| -1.4 | 38 | 100 | 7.0 | ∞ |
| -1.6 | 67 | 100 | 17 | ∞ |
| -1.8 | 87 | 100 | 49 | ∞ |
| -2.0 | 96 | 100 | 167 | ∞ |
| -2.2 | 96 | 100 | 167 | ∞ |
| -2.4 | 96 | 100 | 167 | ∞ |
| -2.6 | 96 | 100 | 167 | ∞ |
| -2.8 | 96 | 100 | 167 | ∞ |
| -3.0 | 96 | 100 | 167 | ∞ |
| -3.2 | 96 | 100 | 167 | ∞ |
| -3.4 | 96 | 100 | 167 | ∞ |
| -3.6 | 96 | 100 | 167 | ∞ |
| -3.8 | 96 | 100 | 167 | ∞ |
| -4.0 | 96 | 100 | 167 | ∞ |

Groundwater level

The half-life period of the cylindrical piles was estimated to be 49 years to ∞, or 49 years if evaluated conservatively, at depths below GL −1.8 m, which was slightly above the upper limit of the groundwater level. In contrast, at depths below GL −2.6 m, the lower limit of the groundwater level, the half-life period was assumed to be ∞, because the oxygen necessary for decay was not available. The half-life period at GL −1.0 m, which was above the upper limit of the groundwater level, was 5.2–19 years. This indicates that decay progressed to around GL −1.0 m in the piles.

## 5. EVALUATION OF MASS LOSS WITH SMALL BLOCK SPECIMENS

### (1) Ratio of remaining mass in parts with cross-sectional loss

**Figure 9** shows the distribution of the ratio of remaining mass of the parts with cross-sectional loss along the depth. The parts with cross-sectional loss were found in the upper elements of the cylindrical piles, which were originally 2.1 m long. However, because the upper and lower elements were not necessarily from the same tree, the density of the lower element may not be suitable as a reference. Although Japanese cedar has large variations in density and strength depending on region and variety, the cylindrical piles excavated in this study were from Japanese cedar trees from the same region.

In **Fig. 9**, there are three points where the ratio of remaining mass exceeds 100%, and this may be because the upper and lower elements originated from different trees. The bulk density measurements of small block specimens also showed that the ratio of the remaining mass exceeded 100%.

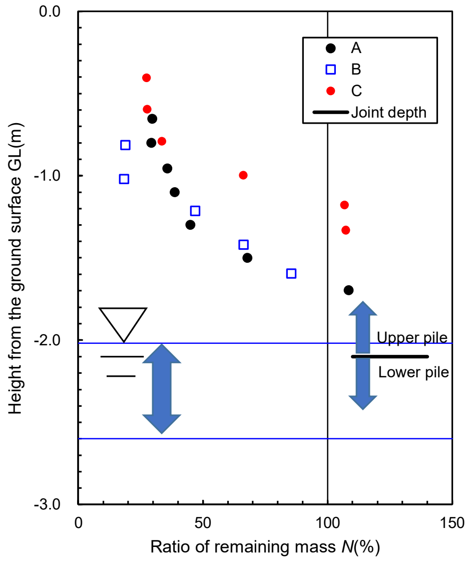

**Fig. 9** Ratio of remaining mass in the parts of the piles with cross-sectional loss.

For each of the parts with cross-sectional loss in the three piles, the ratio of remaining mass increased with depth. This indicated that the diameter of the remaining part increased from the shallower part with heavy losses to the deeper, sounder part.

### (2) Bulk density of small block specimens

**Table 2** shows the results of bulk density measurements of the specimens for the compression tests. The compression tests were conducted in wet conditions above the fiber saturation point, and the oven-dry mass was measured after the compression tests. The volumes of the specimens were estimated based on dimensional measurements before the tests.

**Table 2** Bulk density (kg/m$^3$) and bulk density ratio of small block specimens for compression tests.

| Depth position | Relationship with groundwater | Radial (R-direction) position (standard deviation in parentheses) | | |
|---|---|---|---|---|
| | | Outermost layer b1, d1 | Outermost layer-1 b2, d2, | Outermost layer-2 b3, d3 |
| 3 | Above upper limit | 242<br>(38) | 276<br>(24) | 303<br>(52) |
| 2 | Range of groundwater fluctuation | 287<br>(18) | 291<br>(30) | 295<br>(26) |
| 1 | Below lower limit | 288<br>(20) | 285<br>(27) | 301<br>(34) |
| Bulk density ratio | Relationship with groundwater | Ratio to base bulk density (no.1) | | |
| 3/1 | Above upper limit / below lower limit | 0.84 | 0.97 | 1.01 |
| 2/1 | Range of groundwater fluctuation / below lower limit | 1.00 | 1.02 | 0.98 |

The specimens from the outermost layer were b1 and d1, those from the outermost layer-1 were b2 and d2, and from the outermost layer-2 were b3 and d3 (**Fig. 3**), and the values of the specimens were the average of piles A, B, and C. Because depth position no. 1 was below the lower limit of the groundwater level, decay had not progressed, and thus the bulk density value for no. 1 was used as the base bulk density. The ratios of the values for nos. 2 and 3 to that of no. 1 were calculated.

The bulk density ratio of no. 2 to no. 1 showed that there was no difference in the bulk density between no. 2 and 1. In contrast, the bulk density ratio of no. 3 to no. 1 showed that mass loss occurred in the outermost layer, although there was no cross-sectional loss. Furthermore, for outermost layer-1, the bulk density ratio of no. 3 to no. 1 showed a slight but nonsignificant mass reduction.

**Table 3** shows the bulk density ratios obtained from the split specimens. The bulk density ratios of positions no. 2 or 3 to that of no. 1 were calculated from the averages taken from directions a and c and from cylindrical piles A, B, and C. Because of the irregular shape of the specimens, the volume of the green split specimens was measured by the buoyancy method, in which the specimen was submerged in water and the measured buoyancy was divided by the liquid density.

**Table 3** Bulk density ratio of split specimens(Standard deviation in parentheses).

| Bulk density ratio | Relationship with groundwater | Outermost layer a1, c1 | Outermost layer-1 a2, c2 | Outermost layer-2 a3, c3 | Outermost layer-3 a4, c4 | Outermost layer-4 a5, c5 | Outermost layer-5 a6, c6 |
|---|---|---|---|---|---|---|---|
| 3/1 | Above upper limit / below lower limit | 0.74<br>(0.24) | 0.67<br>(0.33) | 0.85<br>(0.23) | 0.95<br>(0.06) | 0.94<br>(0.16) | 1.04<br>(0.21) |
| 2/1 | Range of groundwater fluctuation / below lower limit | 1.03<br>(0.11) | 1.04<br>(0.07) | 1.04<br>(0.07) | 1.0<br>(0.06) | 0.96<br>(0.08) | 1.06<br>(0.09) |

The ratios of the outermost layer in **Table 3** are the values of split specimens a1 and c1 in **Fig. 3**, and outermost layer-1 represents the values of specimens a2 and c2, which are between 10 mm and 20 mm inside from the outer surface, and so on, and all these values are the average of the three cylindrical piles. **Table 3** shows the results of the bulk density up to 60 mm inside from the outer surface. The results of the two c5 specimens for depth positions nos. 1 and 2 of cylindrical pile C were excluded from the data because their bulk densities exceeded 400 kg/m$^3$, indicating that they contained compression wood.

As with the small block specimens for compression tests, the bulk density ratio of no. 2 to no. 1 showed that there was no mass loss, whereas the bulk density ratio of no. 3 to no. 1 showed that mass loss occurred in the portion less than 30 mm from the surface. The bulk density ratio of no. 3 to no. 1 of the outermost layer was larger than that of outermost layer-1. The outermost layer of the wood blocks from which the split specimens were taken was black, and the density might have been increased by soil components embedded in the wood.

Overall, the results showed that the rate of mass loss tended to decrease from the surface until around 30 mm toward the pith at GL −1m to −1.5 m, that is, above the upper limit of the groundwater level, after 10 years of being buried in the ground. From the results in **Table 3**, mass loss was clearly observed from the outer surface to 30 mm inside in radial direction, whereas at 40 mm or more, mass loss was not clear.

### (3) Half-life period of mass loss of small block specimens

Averaging the results of all bulk density measurements for the part with cross-sectional loss (above depth position no. 3) of the three cylindrical piles (**Fig. 9**), the ratio of remaining mass after 10 years of being buried was 0.533, and the half-life period of mass loss for this part calculated from Equation (3) was about 11 years.

At depth position no. 3, where shape of the outer circumference remained intact, the ratio of the remaining mass of the entire cross section of this position was 0.873 and the half-life period of mass loss was about 51 years, assuming that the 30-mm-thick outermost layer had an average mass loss of 25% and the inner layers had the bulk density of sound wood.

At depth position no. 2, near the top end of the lower element of the cylindrical piles and in the range of the groundwater level fluctuation, there was no significant mass loss observed compared with depth position no. 1 below the lower limit of the groundwater level.

## 6. DISCUSSION

Prior to this study, we reviewed nearly 200 articles, review articles, research publications, and reports on timber pile excavation tests, related timber stakes tests [Note 2], wood exposure tests on forest floors [Note 3], and wood decay tests [Note 4].

The conditions for wood degradation by wood-decaying fungi (excluding soft-rot fungi and erosion bacteria) in the ground can be summarized as follows:

**a)** Free liquid water must be present in the lumen of wood cells and the cells must not be saturated with water.

**b)** Gaseous oxygen not dissolved in water must be present.

**c)** The temperature must be in the range regarded as normal, depending on the species of the fungus. The higher the temperature is, the faster the decay process happens, although if the temperature is too high, the decay process becomes slower again.

**d)** There must be a nitrogen source available to wood-decaying fungi, such as nitrate nitrogen. The carbon / nitrogen (C/N) ratio of wood is insufficient for wood-decaying fungi. Nitrogen sources are dissolved in rainfall or groundwater and are abundant in surface organic soils, whereas they are scarce in inorganic soils deep underground.

**e)** Wood-decaying fungi themselves must be present near the wood for it to be degraded. There are usually various types of wood-decaying fungi in surface soils, which contain organic matter that the fungi can use.

The results of this study are discussed based on these conditions for wood degradation.

Because the bottom end of the lower elements (depth position no. 1) was below the lower limit of the groundwater level, conditions **a)** and **b)** were not satisfied; thus, wood rot caused by wood-decaying fungi did not occur. This has also been confirmed in many other studies.

The position near the top end of the lower elements (depth position no. 2) was in the range of the groundwater level fluctuation, and it is possible that conditions **a)** and **b)** were met for some time periods, and decay might have occurred. However, the bulk density measurements of the small block specimens and the results for the short columnar specimens (half-life period of 167 years to ∞, **Table 1**) indicated no obvious mass loss in this range. Wood decay has been observed in the range of the groundwater level fluctuation where oxygen may have permeated through cracks in the ground[18]. However, in the present study, because the soil at the site has low permeability and is difficult for oxygen to permeate, and there are no building structures to bring in oxygen, condition **e)** of the presence of the wood decaying fungi is not satisfied, and no significant decay occurred in the range of groundwater fluctuation.

The position immediately below the parts with cross-sectional loss in the upper elements (depth position 3) was above the upper limit of the groundwater level. The half-life period at this position estimated from the small block specimens results was about 50 years, and this was consistent with the results for the short columnar specimens shown in **Table 1**. At this depth position, conditions **a)** and **b)** were satisfied. Other conditions, including the presence of wood-decaying fungi in condition **e)**, were also satisfied because the adjacent parts with cross-sectional loss decayed. Because this position was immediately below the parts with cross-sectional loss, decay also occurred in the L direction downward from the parts with cross-sectional loss, not only in the R direction from the outer surface of the cylindrical piles.

According to interviews with relevant people in FFPRI, the heads of the cylindrical piles had been visible at the ground surface until several years before the excavation, and thus all decay conditions **a)** to **e)** were satisfied near the head of the piles. The parts near the head of the piles were exposed to more severe conditions compared with those buried deeper in the ground, as shown in other reports, such as timber stake tests [Note 2)], in which decay occurs most heavily near the ground surface. The diameter of the remaining parts of the cross-sectional loss was nearly equivalent to the diameter of the heartwood, suggesting that only the less durable sapwood might have decayed and had been lost.

According to the standard method of timber pile driving works for liquefaction countermeasures, the pile heads should be buried to a depth below the groundwater level or low-permeability layer. Friction piles and raft foundations for improving cohesive soft clay soil could be installed above the groundwater level, but the wood should be treated with wood preservative. Therefore, the possibility of decay is low for both applications. To our knowledge, this is the only study so far that describes a quantitative evaluation of the ratio of remaining mass of wood used underground, such as timber piles. Although mass loss in the parts with cross-sectional loss is generally large, the only article in which cross-sectional loss of underground timber piles is reported, even qualitatively, is that of Mizuno et al.[16)] They reported that pine piles buried for 107 years as the foundation of a brick viaduct in Tokyo Station had cross-sectional loss up to a depth of 1.5 m from the pile head, and included photographs of the piles. In the abovementioned case study by Murata et al.[18)] in which the timber piles had been in the ground for approximately 60 years, decay was partially observed in the pile heads directly below the structure. However, there have been many cases reported in which the heads of piles that had been in the ground were found to be sound. The soundness of the heads of piles is considered to be greatly affected by the soil type, the location of the log in relation to the structure, and especially the groundwater table conditions, and so on. Therefore, it is necessary to further investigate the influence of these conditions on the cross-sectional loss of timber piles.

Currently, timber piles are not used as foundation supporting piles for large structures [Note 5)], although they are expected to be used again in the future. At present, logs are used only for the foundations of small buildings and for forestry civil works [Note 6)], although not for liquefaction countermeasures or improvement of cohesive soft clay ground. Further data are needed to increase the amount of wood used in the ground and assess its contribution to carbon storage. More data should be gathered through timber pile excavation tests and model experiments. In particular, to allow the carbon storage effect of wood used underground to be included in future national inventory reports, it is important to publish research on wood mass and density, which have not been investigated thoroughly.

## 7. CONCLUSIONS

(1) Assessment of visual grade of decay, Pilodyn penetration tests, compression tests parallel to the grain, and measurement of bulk density were conducted at different depths on cylindrical piles of Japanese cedar that had been buried for 10 years. Degradation due to wood decay was observed in the parts above the upper limit of the groundwater level, and the degree of degradation was higher closer to the ground surface, whereas decay was not observed in the parts below the upper limit of the groundwater level.

(2) There was a difference in the degree of decay above the upper limit of the groundwater level, and the degree of decay was large in the part above a depth of 0.2 m, above the upper limit of the groundwater level. However, in another pile, the degree of decay was large in the part above a depth 1.0 m, which was also above the upper limit of the groundwater level.

(3) The half-life period of mass loss assuming a first-order decay function was estimated based on the reduction of the bulk density of the excavated cylindrical piles. The half -life periods were as follows: about five years in the uppermost parts where cross-sectional loss occurred but some deteriorated wood remained; about 49 years at a depth of 0.2 m, above the upper limit of the groundwater level; conservatively 167 years–$\infty$ in the range of groundwater fluctuation; and $\infty$ at depths below the lower limit of the groundwater level.

(4) The half-life period of mass loss estimated from the data from small block specimens above the upper limit of the groundwater level was about 11 years for the parts where cross-sectional loss occurred, and about 51 years at

the depth where there was no cross-sectional loss above the upper limit of the groundwater level. No clear mass loss was recognized in the range of groundwater fluctuation. These results were similar to those from the measurement of short columnar specimens.

(5) At the depth just below the parts with cross-sectional loss and where the shape of the outer circumference remained above the upper limit of the groundwater level, mass loss was observed in the outer layer of the cylindrical piles. However, no recognizable mass loss was observed in the inner portion 30 mm or more from the surface toward the pith.

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The tests on short cylindrical specimens and the measurement of the ratio of remaining mass of the parts with cross-sectional loss were conducted by Mr. Masao Hamano of the Tobishima Construction Research Institute of Technology.

## NOTES

Note 1) Softwood species form compression wood when trunks or branches are subject to compression stress, resulting in dense wood with a high lignin content.

Note 2) Timber stakes with dimensions of 30 mm × 30 mm × 600 mm are buried in the ground by up to half of their length and pulled out periodically to observe the degree of visual decay and to conduct various tests.

Note 3) The assessment of visual decay and measurement of weight are performed periodically on dead trees and stumps that remain in forests.

Note 4) Small wood specimens (e.g., 20 mm × 20 mm × 10 mm) are decayed under controlled temperature and humidity in a laboratory on unsterilized soil or soil in which wood decaying fungi have been cultured, and the mass loss caused by decay is measured.

Note 5) In 1976, wooden piles were removed from the "Specifications for Highway Bridges"; in 1988, they were removed from the "Recommendations for Design of Building Foundations"; and from the 2001 version onward, it was explicitly stated that wooden piles are not to be included in the recommendations.

Note 6) Timber pile foundations for small buildings and raft foundations for soft clay ground are described in the "Recommendations for Designing of Small Buildings Foundations (1988)" published by Architectural Institute of Japan. Wooden check dams and other river structures for forest conservation projects are described in the "Manual for Construction of Wooden Structures in Forestry Civil Works (2007)".

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