Effects of sediment hardness on the upper limit of the distribution of the burrowing amphipod Haustorioides japonicus on sandy shores: a field evaluation

YOSHITAKE TAKADA1,*, NAOTO KAJIHARA2 & SHINJI SASSA3

1 Japan Sea National Fisheries Research Institute, Fisheries Research Agency, Suido-cho 1–5939–22, Niigata 951–8121, Japan
2 National Research Institute of Fisheries and Environment of Inland Sea, Fisheries Research Agency, Maruishi 2–17–5, Hatsukaichi, Hiroshima 739–0452, Japan
3 Port and Airport Research Institute, 3–1–1 Nagase, Yokosuka 239–0826, Japan

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Abstract: Relationships between the sediment hardness and the upper distribution limit of the burrowing amphipod Haustorioides japonicus were examined on 18 sandy shores in Niigata and Toyama prefectures, on the Japan Sea coast. Sediment hardness was measured by three methods (using a vane tester, a digital force gauge, or a cone penetrometer) and compared with the estimates from a previous laboratory experiment. Results showed that the vane tester measurements of the hardness of the sandy sediment corresponding to the upper distribution limit on the shores represented a similar value to the measurement obtained in the laboratory. Some similarities between the measurement mechanisms of the vane tester and the burrowing behavior of the amphipods may explain the results. Consideration of the mechanism of hardness measurement will improve understanding of the relationships between sediment hardness and the distribution of burrowing animals on sandy shores.

Key words: penetration resistance, physical environment, sediment hardness, vane shear strength, zonation

Zonation of benthic animals on sandy shores is well documented (McLachlan & Jaramillo 1995, McLachlan & Brown 2006). Distributions of single species or assemblages of several species are recognized which correspond to spatial and temporal gradients of the physical environment (Wardiatno et al. 2003, Defeo & McLachlan 2005, Lercari & Defeo 2006). Because of the temporally changing nature of the physical environment on sandy shores, animals living there need to respond to these temporal changes. For burrowing animals to respond appropriately to temporal changes of environmental factors, it is important to search for or encounter suitable zones to burrow into.

The amphipod Haustorioides japonicus Kamihira lives in the swash zone of sandy shores burrowing into the surface layer of the sediment (Kamihira 1992, Suzuki et al. 2013). This species has several generations in a year and shows its maximum density in the summer season. The animals catch organic particles drifting with incoming and receding waves by extending their tentacles upright from the sediment surface to feed on them. As wave and tidal height fluctuate temporally, they change their feeding position on the shore. However if the sandy sediment is too hard, it is not possible for them to re-burrow into the sediment when they are washed out from the bottom sediment or to adjust to an appropriate feeding position on the surface layer of the sediment. Therefore sediment hardness is considered to be a critical physical factor affecting the distribution range of burrowing amphipods on sandy shores.

Although the importance of sediment hardness has long been recognized (e.g. Perkins 1958), until recently there has been little attention paid to the mechanical properties of sediment hardness (Sassa & Watabe 2008). Several methods to measure sediment hardness have been proposed so far, but they employ different principles, so their properties require careful evaluation in the context of the burrowing processes of animals on the shore (Sassa et al. 2011).

A series of laboratory experiments (Kajihara & Takada 2008) revealed the relationships between the burrowing success of H. japonicus and sediment hardness measured by three methods: vane shear strength, penetration resistance by a push rod, and penetration resistance by a free-fall cone. When H. japonicus was placed on the surface of sediments of experimentally controlled hardness, the results showed that increasing sediment hardness decreased the probability of individuals burrowing successfully. Therefore, the first aim of the present study is an evaluation of these methods of measuring sediment hardness on sandy shores in the natural environment. The second aim is to evaluate the results of laboratory
experiments by demonstrating the effect of the sediment hardness on the upper limit of the distribution of the *H. japonicus* on sandy shores.

Field surveys were carried out at 18 sandy shores (Fig. 1) on Sado Island and the Japan Sea coast of Honshu from Toyama to Niigata during summer in 2008 and 2009. The surface sediment (down to 3 cm depth) of these shores was largely composed of fine sand: medium phi ranged from 0.88 to 3.02. Transects were performed on each shore, perpendicular to the shoreline from the drift line to the swash zone, sampling at 1 m intervals. At each sampling point, three sediment columns (10 cm in diameter, 10 cm in depth) were collected using a cylindrical core sampler. Sediment samples were sieved (1.0 mm mesh) and the presence or the absence of *H. japonicus* was recorded. On each transect, the upper limit of the vertical distribution of *H. japonicus* was determined between the last point where no individual was detected and the first point where at least one individual was obtained. Then the sediment hardness was measured at these two points.

Following laboratory experiments (Kajihara & Takada 2008), three different devices for measuring sediment hardness were used: a vane tester (Pocket vane tester, Eijkelkamp), a digital force gauge (FGC-5, Nidec-Shimpo Co., Ltd.), a cone penetrometer (DIK-5585, Daiki Rika Kogyo Co., Ltd.). The vane tester measures the shear strength (kPa) of the surface (uppermost) layer of sediment using a vane of 0.5 cm depth. The digital force gauge measures the penetration resistance (N/5 cm) of a rod with a conical tip (1.0 cm diameter) to a depth of 5 cm into the sediment. The cone penetrometer measures the penetration resistance (kPa) by a free-falling cone (107 g) into the sediment surface. Logistic regression equations were applied to the presence or absence (1/0) of *H. japonicus* against each of the three measurements of sediment hardness.

![Fig. 1. Location of the study sites (dots). Three sites were located close together (dots indicated by an arrow).](image1)

![Fig. 2. Presence (1) and absence (0) of Haustorioides japonicus on sandy shores (circles) and the estimated curves of logistic regressions against the three measurements of sediment hardness: A, vane tester; B, digital force gauge; C, cone penetrometer. Regression equations are shown with the value of 50% probability of presence (P50). The hardness values with 50% probability of burrowing (B50) estimated from Kajihara & Takada (2008) are also shown (crosses).](image2)

Statistically significant regressions ($p<0.05$) were obtained for the three different methods of measuring sediment hardness (Fig. 2). Probability of the presence of *H. japonicus* decreased with increasing sediment hardness for all three methods. However, the gentle slope of the regression curve of the cone penetrometer (Fig. 2C) showed that the fitness of the regression was not good. Using the estimated parameters of
the logistic regressions, critical hardness values for a 50% probability of presence (P50) were estimated (Fig. 2).

In previous laboratory experiments (Kajihara & Takada 2008), the probability of individuals successfully burrowing was expressed as functions of sediment hardness, from which hardness values for 50% probability of burrowing (B50) were calculated. For all three different methods of measuring the sediment hardness, the B50 values were smaller than those of P50, but the differences between B50 and P50 were different among the three measurements. For the vane tester, B50 (2.36 kPa) was similar to P50 (2.70 kPa), while B50 for the digital force gauge (14.3 N) was less than half of P50 (32.0 N), and B50 for the cone penetrometer (24.0 kPa) was 60% of P50 (39.7 kPa).

The vane tester yielded the best estimates for the upper distribution limit of H. japonicus on the shore within the three measurements of the sediment hardness. Two possible factors for this good performance may be the burrowing depth of H. japonicus in the sediment and the mechanism of the measurement method. Most individuals of H. japonicus occur within 2 cm of the surface of the sandy sediment (Kamihira 1992), so, hardness measurements effective at depths below 2 cm will not contribute to better estimates for the presence of H. japonicus. The burrowing behavior of H. japonicus (Kajihara & Takada 2008) indicates that sediment is cleaved and shifted aside when they burrow, rather than applying force perpendicular to the sediment surface. Therefore, their burrowing mechanism is probably more closely correlated with the way the vane tester presses against the sediment, rather than relying on direct pushing against penetration resistance as employed by the cone penetrometer or the digital force gauge. Recently, Sassa et al. (2013) demonstrated that the dynamic state of suction, that is, negative pore water pressure relative to atmospheric air pressure, controls the physical properties of sandy sediment and hence affects the vertical distribution of burrowing peracarids (which include H. japonicus). Observations on suction as well as hardness will present new insights into sediment-animal relationships in future studies.

The three methods of measurement for sediment hardness employed different mechanisms. The vane tester measured the shear strength of the surface of the sediment to a depth of 5 mm. Both the digital force gauge and the cone penetrometer measured the resistance pressure for penetration from the surface of the sediment. The digital force gauge measured the forced resistance to a depth of 5 cm, while the cone penetrometer used a free-falling cone. If the sediment is composed of several layers with different hardnesses, the cone penetrometer is more sensitive to differences in the surface layers than the digital force gauge. If the upper 1 cm layer is hard, the cone would stop within the 1 cm layer, but the rod of the digital force gauge can be manually inserted to a depth of 5 cm. The sediment measured in the present study has a hard layer at around 5 cm depth which may increase the value of the digital force gauge and disproportionately increase the P50 values compared to the B50 values obtained in the laboratory experiment of Kajihara & Takada (2008). An additional drawback of using the cone penetrometer is that the relationship between measurement and resistance of penetration of the cone is non-linear, which produces a non-normal distribution of errors in measurement values.

Many studies have focused on sediment hardness as one of the factors affecting the distribution of sandy shore animals. In the present study, vane tester measurements corresponded well to the upper limit of H. japonicus. In another study, the digital force gauge gave a good regression to the ignition loss of muddy sediments (Kajihara et al. 2010). Penetration pressure by a rod has also been found to provide a good estimate of human trampling damage on seagrass rhizomes (Eckrich & Holmquist 2000). The most appropriate method of measuring substrate hardness may therefore depend on the particular sedimentary habitat and/or organisms being studied and should be selected carefully according to the particular field conditions and animals under investigation. Hence, consideration of the mechanism of hardness measurement will improve understanding of the relationships between sediment hardness and the distribution of burrowing animals on sandy shores.

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