Geology is the key: Understanding the liquefaction susceptibility of Niigata City soil

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ABSTRACT

The Niigata ***M***7.5 Earthquake of 1964 remains uniquely important among field case histories for understanding liquefaction triggering and manifestations. Much has been written about the Kawagishi-cho strong motion record, the Niigata case histories of seismic-soil liquefaction triggering, and the post-triggering lateral spread displacements. This paper explores a new and different perspective on the disaster - the geologic setting and geomorphic processes reworking Holocene sand units that ultimately create the most severe liquefaction effects during the earthquake. Across the city, liquefaction was most pronounced in fluvially-reworked sands derived from three aeolian and barrier island dune fields upriver and along the coastline. The largest source of beach and aeolian sand material that liquefied in 1964 is a mid-Holocene maximum transgressive barrier island that deposited fifty–sixty meters of sand along the then coastline five-eight-thousand years ago. Tectonic-downwarping and -subsidence of the Echigo Plain has allowed for delta-progradational processes to build out a thick sedimentary prism beneath the current location of Niigata City. Within this prism, the Shinano and Agano Rivers have eroded and fluvially-redeposited these barrier island sands, and those of a closer-in two-three-thousand-year beach-ridge deposit, beneath districts of the city. Most recently, for human-placed fills the materials are sourced almost entirely from modern coastal beach-ridge and sand dune deposits fronting the Sea of Japan. More than any other factors, these geologic conditions and geomorphic depositional histories controlled the locations and severity of soil liquefaction during the 1964 event. Today, these geologic units persist as a future risk to infrastructure of Niigata City.

Keywords: Niigata, geology, aeolian, dune, fluvial, liquefaction susceptibility

1 INTRODUCTION

The 1964 Niigata ***M***7.5 earthquake remains a watershed event in the field of geotechnical earthquake engineering. Soil, liquefaction, settlements, and lateral displacement had a devastating effect on the city's infrastructure, and these effects have been well documented in the literature. This paper explores the critical importance of regional Holocene geology beneath the Echigo plain that set the stage for the 1964 Niigata disaster and continues to threaten the city, today. This aspect of the disaster is not unique to Niigata city - geology largely controls the damage patterns observed of all the earthquakes effecting the Tōhoku coastline of the Sea of Japan over the last eighty years (e.g., Fukui, 1948; Niigata, 1964; Nihon kai-Chubu, 1983; Niigata Chuetsu, 2004; Niigata Chuetsu-Oki, 2007).

2 REGIONAL SETTING FOR THE DISASTER

The west side of Tōhoku is tectonically bounded by the Niigata-Kobe Tectonic Zone (NKTZ) and separates the Eurasian and Okhotsk/North American plates (Tada et al., 1997; Sagiya et al., 2000) and is the principal source of regional earthquakes. Niigata city is located on the western edge of the Echigo Plain, a large coastal alluvial plain facing the Sea of Japan. The Shinano, and Agano Rivers (Figure 1) are the main-stem river systems of this plain and their coastal low-land deposits suffered severe liquefaction effects in 1964.

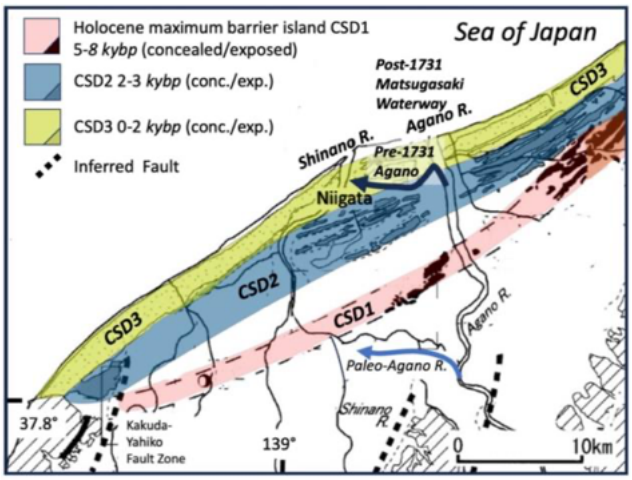

Figure 1. Mid-Holocene barrier island, and distribution of coastal sand dunes of the Echigo Plain (modified from Urabe, 2004)

To the surprise of researchers, the up-river sections of these rivers were not affected by liquefaction -

following the Niigata Chuetsu event of 2004 (Bardet et al. 2004; Rathje et al, 2006), nor the Niigata Chuetsu-Oki earthquake of 2007 (Kayen et al., 2009). Important geologic and geomorphic features on the Echigo Plain and absent on upriver sections explain this distinction in liquefaction performance.

2.1 Coastal Sand Dune I (CSD1)

The Echigo Plain is unusual in Japan for the thickness of the alluvial prism of Quaternary sediment (up to 140 m) and is the result of tectonic downwarping and subsidence. During the early-Holocene maximum transgression of the Sea of Japan onto the plain, between 5,000 and 8,000 years before present (y.b.p.), a 50-60-meter-thick coastal barrier-island of beach deposits and aeolian dune sand fronted the Sea (Urabe, et al. 2004). Urabe et al. (2004) termed this 'Coastal Sand Dune I', and termed CSD1, here (Figure 1&2).

Today, these deposits are between 5 and 8 kilometers from the coastline, eroded to the elevation of the plain, and in most places concealed by a veneer of recent finer-grained flood plain deposits (Figures 1 & 2). The unit CSD1 is observed at the surface at Kameda in Kohnan-Ward, and Ota and Sasaki in Kita Ward. Unit CSD1 is composed of well-sorted aeolian deposits of fine-, medium-, and course-grained sand and beach ridge sands. Standard Penetration Test (SPT) blow counts in the CSD1 sand is typically between 20 and 40 blows (medium stiff-stiff; Urabe, et al. 2004). In 1964, these deposits exhibited minimal liquefaction effects. The upper-bounding layer of the CSD1 unit is capped by the 5,000 y.b.p. Numazawa volcanic ash deposit, an important diagnostic tephra-chronologic stratigraphic-boundary of the Echigo plain (Numazawa Collaborative Research Group, 1999).

In mid-Holocene time the CSD1 coastal barrier island system extended continuously through the Echigo plain with one incision, the Paleo–Shinano River. The paleo-channel of the Agano River has not been found and likely indicates that it was connected to the Shinano River system south of CSD1 during the mid-Holocene transgression (Figures 1 & 2; Urabe, et al. 2004).

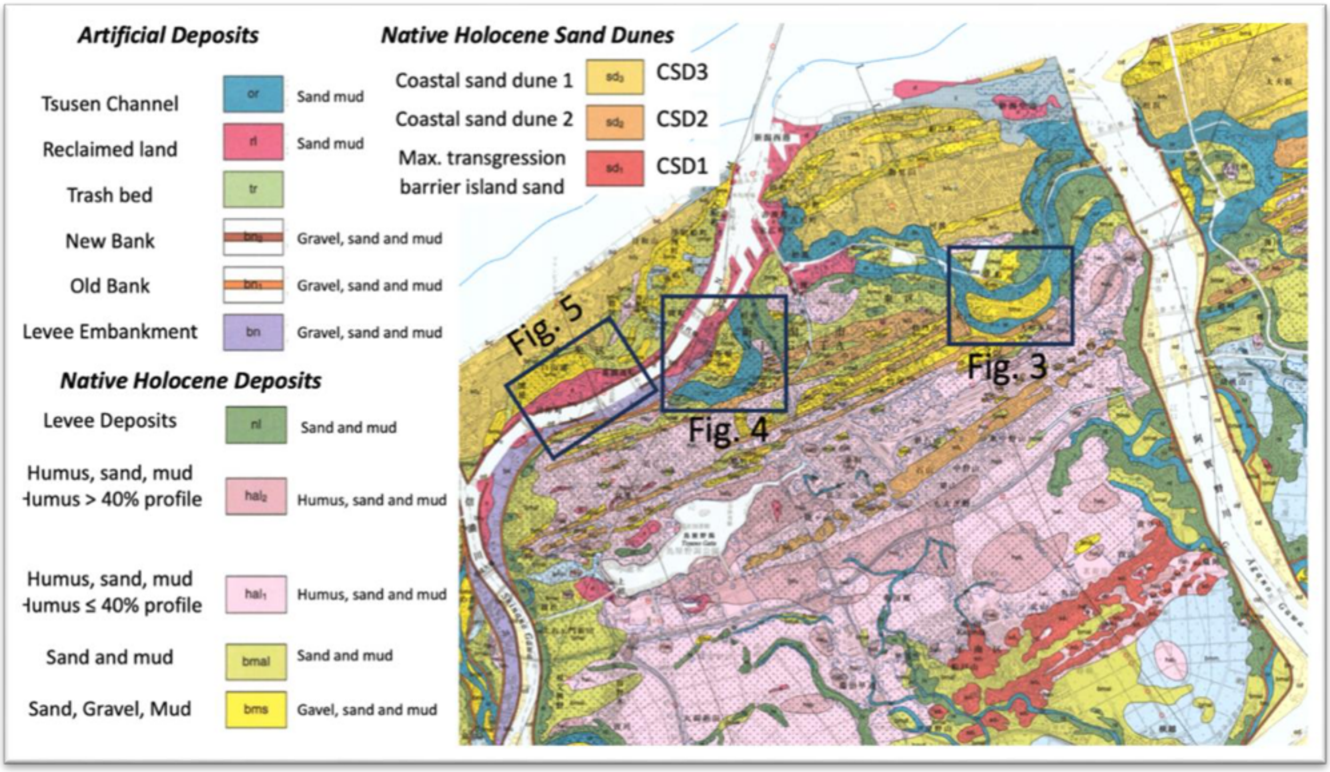

Figure 2. Modified geologic map of the Geological Survey of Japan for Niigata and Uchino, GSJ-G050-07009 (Kamoi et al., 2016). Legend is shortened and simplified to present only the Holocene deposits of the Echigo Plain. Full map and legend are available online at: https://www.gsj.jp/data/50KGM/JPG/GSJ_MAP_G050_07009_2016_200dpi.jpg

2.2 Coast Sand Dune II & III (CSD2 & CSD3)

Continued tectonic tilting and subsidence of the Echigo plain has down-warped the bedrock to the west between 5 and 18 m in the last 5,000 years, a rapid subsidence rate of one-to-four meters per thousand years. The subsidence is due to active tectonics on the western margin of the plane due to the locally active Kakuda-Yahiko fault zone. Subsidence has allowed for rapid progradation of deltaic-beach ridge deposits toward the present-day coastline. CSD2 was an active beach ridge zone between 3000 and 2000 y.b.p. and is exposed at the surface throughout the city from the right bank of the Shinano River to the plain northeast of the current outlet of the Agano River. West of the left-bank of the Shinano

River, the CSD2 deposits are concealed beneath flood plain deposits due to the active subsidence. The Coastal Sand Dune III (CSD3), with an age range of 2000 y.b.p. to the present, extends broadly across the active present coastline (Figures 1 & 2; Niigata Ancient Dune Research Group, 1974). Sands within CSD2 and CSD3 are derived from aeolian dune deposition and accretion of beach sand derived from littoral processes along the coast, and from sands eroded from CSD1 by the Shinano and Agano Rivers. As with CSD1, these more recent sand dune deposits have moderate to stiff well-sorted sands with SPT blowcounts of 20-40, and manifested little liquefaction related damages in 1964.

3 SHINANO AND AGANO RIVERS

The modern Echigo plain is drained by its two largest rivers, the Shinano and Agano with their separate mouths at the Sea of Japan. Historically, and in middle-late Holocene times, this was not the case. Before 1731 and the early pre-1731 Tokugawa Shoganate period, the Agano River migrated northward to its present course but was blocked from the sea by Coastal Sand Dune III (CSD3) in the vicinity of present-day Niigata Airport. Approximately one kilometer south of the Sea, the Agano River bent sharply westward and joined near the Shinano River near present day Bandai Island. Throughout the late Holocene time these two rivers scoured sand from the native Holocene deposits CSD1 and CSD2 to build natural levees and line the river floor of the meandering river channels.

A land development policy of the eighth Tokugawa Shogun Yoshimune sought to stabilize river depths and flows on the Agano and Shinano Rivers for shallow-draft shipping, and in 1731 opened the Agano River to the Sea of Japan at the Matsugasaki waterway, excavating through the natural barrier of CSD3. The natural flow of the Agano river was subsequently cut off from the Shinano River by a system of canal locks and weirs completed by the early 1900's. The Agano river course was reduced to the much-narrower Tsusen (Old) River. The surrounding lowland fluvial sand deposits and the floodplain of the Agano River, derived from reworked deposits of CSD1 and CSD2, were filled and developed. At the time of the 1964 Niigata earthquake, the natural 0.5–1.5 km wide floodplain of the Agano River had been trained and channelized into a constrained 10-m wide canal termed the Tsusen River. Behind protective levee structures, the frontage along the Tsusen River was filled and urbanized the entire stretch of river from Chuo Ward -to-Higashi Ward.

After massive flooding in 1917, the Ohkouzu Diversion channel was excavated in 1922 upriver of Kawagishi-cho to reduce potential flooding on the Shinano. This helped the reclamation and development of the lower Shinano River basin.

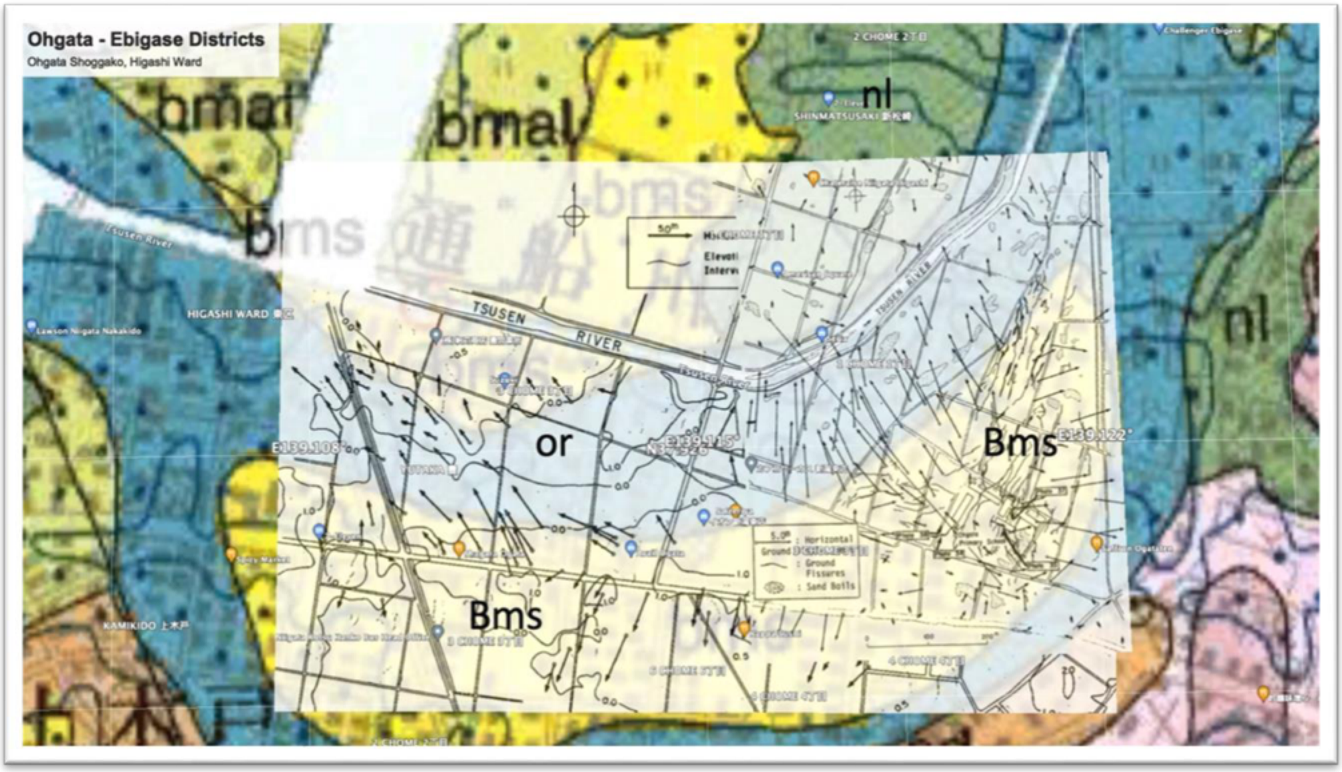

Figure 3. Overlay of Hamada (1992) displacement vector and surface manifestation figures for the Ebigase-Oghata district, Niigata. The large displacements occur almost entirely in native mid-late Holocene sand unit Bms

4 LIQUEFACTION SUSCEPTIBILITY

The process of opening the Matsugasaki waterway in 1731 and abandoning the Agano River confluence with the Shinano River at Bandaijima profoundly worsened the conditions for future soil liquefaction in Niigata City. Natural processes and governmental policies that led to the re-alignment of the riverbank along the Shinano River, and allowed for development behind the new banks also greatly exacerbated the liquefaction problem (covered in the section on Kawagishi-cho, below). Numerous excellent early works by the JSCE, Universities, utilities, and Institutes (e.g., PWRI) and air photos collections recording damage from the 1964 event have been used to identify sites of surface manifestations of liquefaction. Seminal geotechnical studies on the liquefaction resistance of Niigata soil (e.g., Ishihara and Koga, 1981) have laid the groundwork for much of the engineering methodologies used today to assess liquefaction potential.

An important contribution to the understanding of liquefaction damage at Niigata was a chapter of NCEER Technical Report 92-001 by Hamada (1992). Professor Hamada, in the style of that remarkable report on the Fukui 1948 Earthquake by Collins and Foster (1949), used air photos and ground observations to map liquefaction surface manifestation and horizontal lateral spread displacement vectors on for neighborhoods most severely damaged during the earthquake.

4.1 Ohgata & Ebigase Neighborhoods, Higashi Ward

Ohgata & Ebigase neighborhoods are located on the south side of the Tsusen River canal. Ohgata Primary school (Shogakko) is located on the slightly elevated former levee of the Agano River entirely in native unit Bms (See yellow geologic unit Bms in the legend in Figure 2), a deposit of CSD1 and CSD2 aeolian and beach ridge sands reworked and redeposited by the river processes (Figure 3).

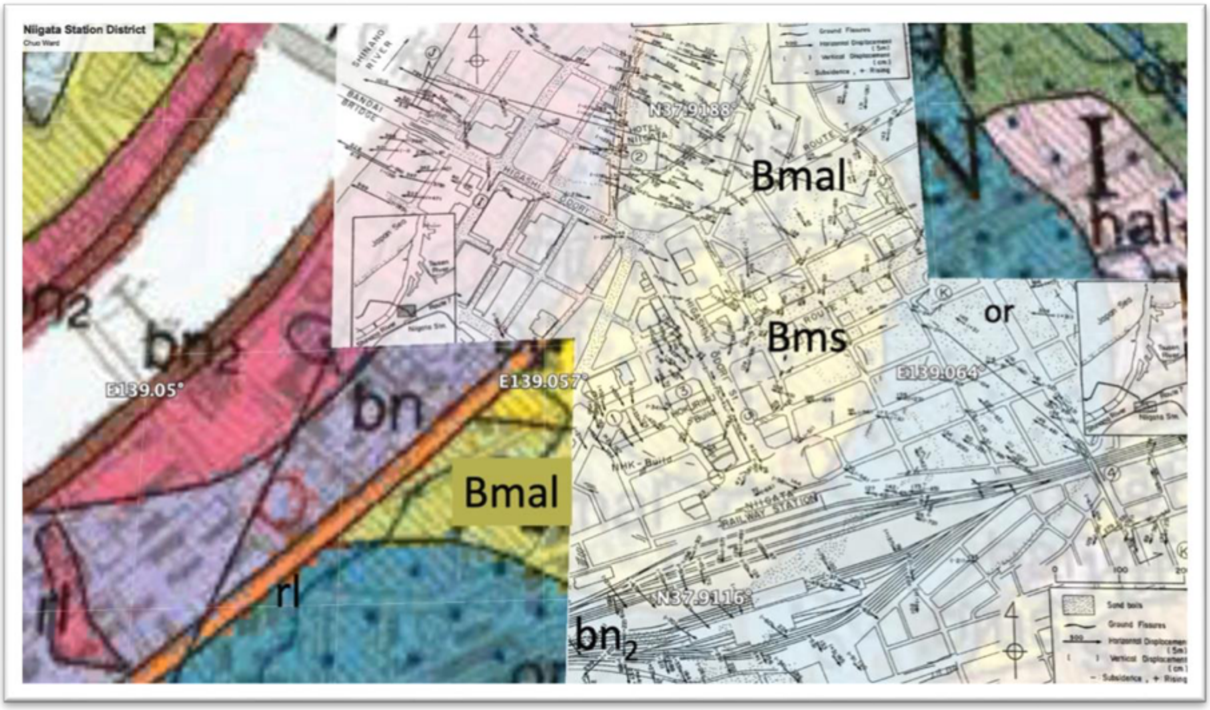

Figure 4. Niigata Station and Hotel area, Chuo Ward geologic map and overlay of Hamada (1992) displacement vectors are directed almost entirely *away* from the Shinano River in mid-late Holocene unit Bms and Bmal.

The ground displacements vectors of Hamada (1992) record the direction of the horizontal movement and amplitude in centimeters. The horizontal displacements occur primarily within the natural levee deposits northward toward the Tsusen River but also south and eastward toward back-marsh areas *away* from the river. This downslope movement, here and for the other sites discussed, occurred downslope on slopes less than 1°. Horizontal displacements from the slight topographic high at Ohgata school were as large as 6 m toward Tsusen River and 5 m away from the river to the south. Remarkably, liquefaction displacements, even in the filled areas away from the Bms levee deposits were negligible on both sides of the river. At Ohgata Primary School (Figure 3) the horizontal displacements occurred in all direction's downslope. The natural levee was riddled with a dense network of lateral spread fissures.

4.2 Niigata Station and Hotel Niigata, Chuo Ward

The neighborhood between the Bandai Bridge on the Shinano River and the JR Niigata Station was one of the most heavily damaged areas of Niigata, with many liquefaction-related structural failures. The district is on the right bank (south side) of the Shinano River and centered along Higashi Dori Street (Figure 4). Approximately 200m south of the Shinano River, the old right bank divides a zone containing a thin prism of newly placed fill that widens toward the modern river course and overlies native deposits, from the surficial native soils south of the old bank. Those native deposits, on either side of the old bank, are reworked aeolian dune sands and beach-ridge deposits CSD1 and CSD2 eroded and redeposited by the pre-1731 course of the Agano River and the paleo-Shinano River.

Horizontal ground displacement of the zone of reclaimed land north the old historic riverbank, Bn2 (see Figure 2) displace toward the river, whereas most of the vectors south of the old riverbank displace *away* from the Shinano River toward the south and south-east, including Hotel Niigata and Niigata station that moved about 3-4 meters. The density, amplitude, and direction of the southeasterly displacements east of Higashi Dori St. near Hotel Niigata are particularly striking. Near JR Niigata Station, the ground also settled 0.5 to 1.0 m. The geologic map in Figure 4 clearly indicates the high liquefaction susceptibility of native geologic units Bmal and Bms, alternating units of sand Gravel, sand, and mud (see legend in Figure 2). Again, these sands derive from reworked units of the barrier island and more recent beach-ridge deposits.

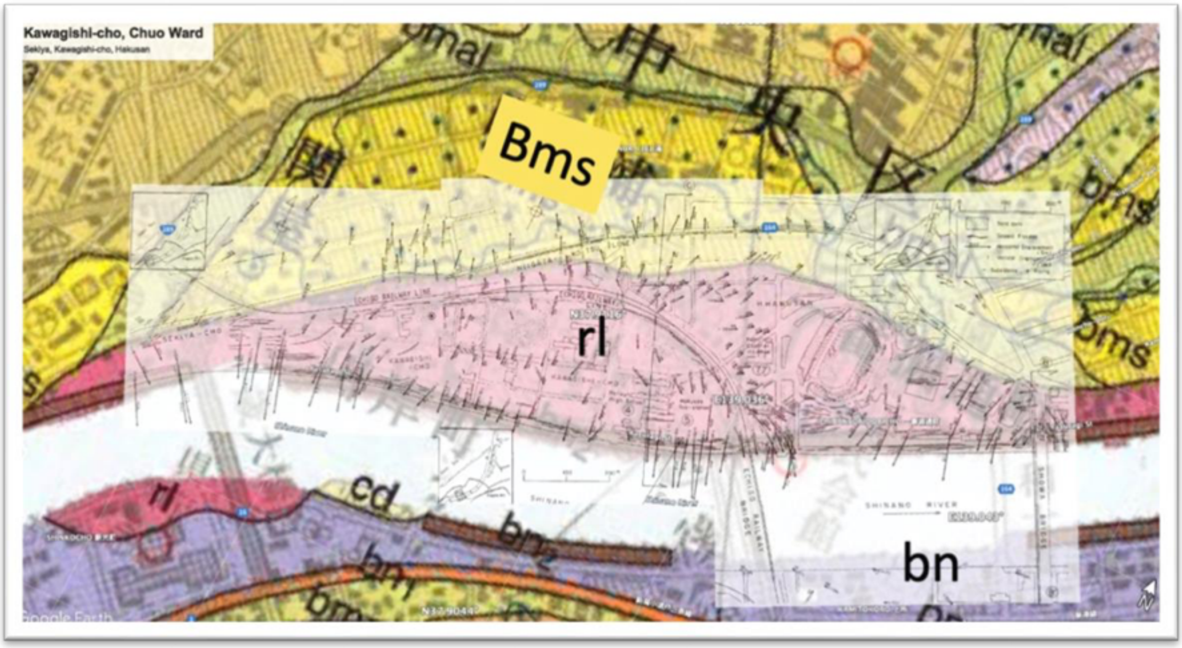

Figure 5. Kawagishi-cho, Hakusan, and Sekiya areas on the left-bank of the Shinano River, Chuo Ward. GSJ geologic map and overlay of Hamada (1992) displacement vectors and surface manifestations. The large displacement vectors are directed away from Bms soil occupied by the Echigo railway.

4.3 Kawagishi-Cho District, Chuo Ward

Kawagishi-cho is perhaps the most famous neighborhood in Niigata City, known because of the remarkable bearing capacity failures of apartment buildings, and for the seminal work done there on the liquefaction resistance of soil. For example, large diameter sample soil testing by Ishihara and Koga (1981) found the zone of soil liquefaction extends continuously through the soil profile from 2.5 meters to 13.5 meters. There and in other reports, the authors note that the surficial deposits at Kawagishi-cho were reclaimed by placement by un-engineered dumped fills. This is not to suggest that the liquefaction zone (Ishihara & Koga, 1981, Figure 18a and 18b) only extends through placed fill. A detailed political and engineering history of the development of Shinano Rive and more broadly the Echigo Plain waterways can be found in Chino and Okuma (1992). In their study, measurements of the water depths at the confluence of the Shinano and Agano Rivers in 1697 were approximately 7 meters at the center of the channel and 4.5-6 meters at the left and right banks. Kawagishi-cho is 3.5 kilometers upriver of the confluence where the river was likely in shallower water. Chino and Okuma (1992) noted that siltation by blowing CSD3 aeolian dune sands has always been problematic for maintaining water-depths for shallow-draft shipping on the Shinano River. By 1903, riverbank work narrowed the Shinano River to increase the flow velocity and maintain 6 m of water depth. In 1911, much of the focus of waterway improvements were directed toward maintaining and upgrading ports downriver at Bandai Island, Rinko Wharf, and Niigata wharves near the Tsusen River locks.

The above discussion of the evolution of the Port of Niigata is to argue that the water depth at Kawagishi-cho could not have been more than 6 m, one-quarter of the liquefaction zone profile presented by Ishihara and Koga (1981) and may have been several meters less. The liquefaction at Kawagishi-cho occurred in both reclaimed and native-ground. This is evident in the cross-river profiles of Hamada (Figure 8 & 9, 1992). In these figures, the depth-range of the liquefaction zone occurred both in reclaimed and native sandy soil (termed As-1 and As-2 by Hamada). Indeed, the liquefaction at

Kawagishi-cho occurred within both reclaimed and native river-bed deposits of the Shinano river channel as it existed during the former Tokugawa shogunate-era (1603-1868). Hamada notes that the former river channel roughly coincides with the area where fissures, sand boils, and large ground displacements that move southward toward the modern riverbank. On the other hand, the marginal and non-liquefaction conditions on the right (south) bank site presented by Ishihara and Koga (1981) and Hamada (1992) are not in the former river deposits but the old riverbank and floodplain (Hamada, 1992, Figure 8b). Riverbed soils As-1 and As-2 underlying Kawagishi-cho are the result of fluvial reworking and accretion of upriver dune and beach sand deposits CSD1 & CSD2, and windblown aeolian sands from CSD3.

The map in Figure 5 shows that liquefaction displacements are moving away from the high ground of the Echigo railway toward the Shinano River to the south, and *away* from the river to the in former riverbed fluvial sand Bms. The soil to the south of the railway is mapped as surface reclaimed land, but this represents a thin veneer, 1-6m, of placed-fill overlying thicker sections of Bms native soil (unit rl, see legend in Figure 2).

5 CONCLUSIONS

The Niigata Earthquake and liquefaction damages reinforce observations made by Youd and Hoose (1977) nearly fifty years ago: geology largely controls liquefaction performance of soil and its associated ground failures. At Niigata City, the tectonic setting, environment of deposition and reworking, and human modifications set the stage for dramatic liquefaction effects. The backdrop that sets the conditions prior to the disaster are: [1] a large 50-60m thick barrier island sand deposit (CSD1) on the Echigo plain deposited 5000-8000 y.b.p.; [2] rapid tectonic downwarping of the coastline creating space for progradation of sediment westward across the plain; [3] paleo-Agano river joining the Shinano River upstream of relatively dense and non-liquefiable CSD1, allowing for enhanced erosion and redeposition of looser fluvial sands downstream; [4] Agano River migration northward, cutting through CSD1 at present day Higashi Ward and reconnecting with the Shinano downstream at Bandai Island. This allows for fluvial-redeposition of loose sands of CSD1 and younger beach ridge deposits CSD2 across present day Tsusen River corridor (Ohgata, Ebigase, Niigata Station and Higashi Dori-Bandai Bridge areas); [5] active aeolian processes along the coastline send large volumes of CSD3 sand into the Shinano River; and finally, [6] human influences training and reclaiming land along the Shinano, Tsusen, and Agano river systems placed highly susceptible materials directly beneath civil infrastructure systems of Niigata City.

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