Field Observations and Microtremor Measurements at Inca Historical Sites and Constructions in Peru

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Abstract

This report documents the preliminary results obtained from the measurement of ambient vibrations performed at historical Inca sites and constructions in Cusco, Peru. The measurements were carried out during 19-24 June 2004. Locations selected for observation and measurement were: Machupicchu, Coricancha (Cusco city), Sacsayhuaman, Tambomachay and Pisac.

Introduction

About 500 years ago, the Inca culture reached the peak in its development, which was just before the arrival of Spaniard conquistadors. By the time, the Incas had integrated a vast empire that stretched from the Maule river in Chile to the northern Ecuador along the western side of the Andes mountain. This territory, as in present days, had continuously been exposed to natural disasters such as excessive rainfalls, earthquakes, landslides, floods, etc. In spite of such impending disasters, the Incas were able to develop techniques of construction to withstand such natural forces. The awe-inspiring cities and road networks that remain intact to this day serve as witness to their acumen in construction.

The structural system of their construction involves the use of adobe (sun-dried clay bricks), roughly shaped stones laid with mud mortar and finely shaped stones. They also used mud and clay as mortar for surface finishing. Finely shaped stone masonry was used for important building like temples, administrative structures and king's residences. In this type of construction, the adjacent stones are carefully shaped and fit snugly against each other without the use of mortar.

The Inca's stone structures have survived earthquakes that have occurred in the region over the years. Preliminary attempts to investigate the behavior of typical Inca stone masonry wall components under the action of earthquakes has been initiated by the Department of Architecture and Environment Systems, Akita Prefectural University, since 2002. For this, the seismic hazard of a representative zone of the Inca territory was undertaken. The selected zone includes the city of Cusco (capital city of the Inca Empire) and the citadel of Machupicchu (the so called lost city of the Incas). Both of these places are UNESCO world cultural heritage sites. The seismic hazard analysis aimed at estimation of the characteristic seismicity in view of various ancient stone masonry structures located in the region. As a second step, typical elements of Inca construction were analyzed by simple method to understand the structural behavior. Basically, the investigation was limited to stability of typical elements under the earthquake action evaluated from hazard analysis.

Evaluation of the vulnerability of the heritage structures to prevalent earthquake hazard is an

important aspect essential for risk analysis. As an attempt to verify the preliminary analysis and to establish the criteria for future vulnerability studies, a plan for microtremor measurements was developed to permit estimation of the dynamic characteristics of Inca constructions and local sites. Measurements were performed as per the plan during June 19 to 24, 2004. The selected places and measurements were as follows:

1) Machupicchu citadel:
   1.1. Plaza (square): Ground vibration measurement (vertical sensors)
   1.2. Terraces of Intihuatana: Vibration of terraces structures (horizontal sensors)
   1.3. Temple of Three Windows: Structure vibration
   1.4. Principal Temple: Structure vibration
   1.5. Temple of the Sun: Structure vibration
   1.6. Building No 7 of Group 2: Gable wall and structure vibration
   1.7. Building No 2 of the Group of the Mortars: Gable wall and structure vibration
   1.8. Terraces at low part of Group 13: Ground vibration (horizontal sensors)

2) Coricancha
   2.1. Star Temple (Chasca): Structure Vibration
   2.2. Temple of Thunder (Illapa) : Structure Vibration
   2.3. Tower of Santo Domingo Church: Structure Vibration
   2.4. Interior Yard (Ceremonial Fountain): Ground vibration measurement (vertical sensors)
   2.5. Exterior Garden (Sacred Garden of Sun) : Ground vibration measurement (vertical sensors)

3) Sacsayhuaman:
   3.1. Ground vibration measurement (vertical sensors)

4) Tambomachay (Bath of the Inka):
   4.1. Structure vibration

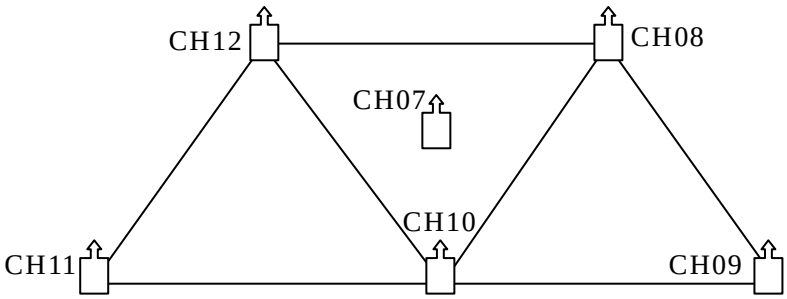
5) Pisac:
   5.1. Typical construction: Structure vibration

Additionally, measurements of micro vibration were performed at the following places:
- One building unit of the Hospital ESSALUD of Cusco: Structure vibration
- Ground vibration measurement at National University of Cusco (earthquake recording station)

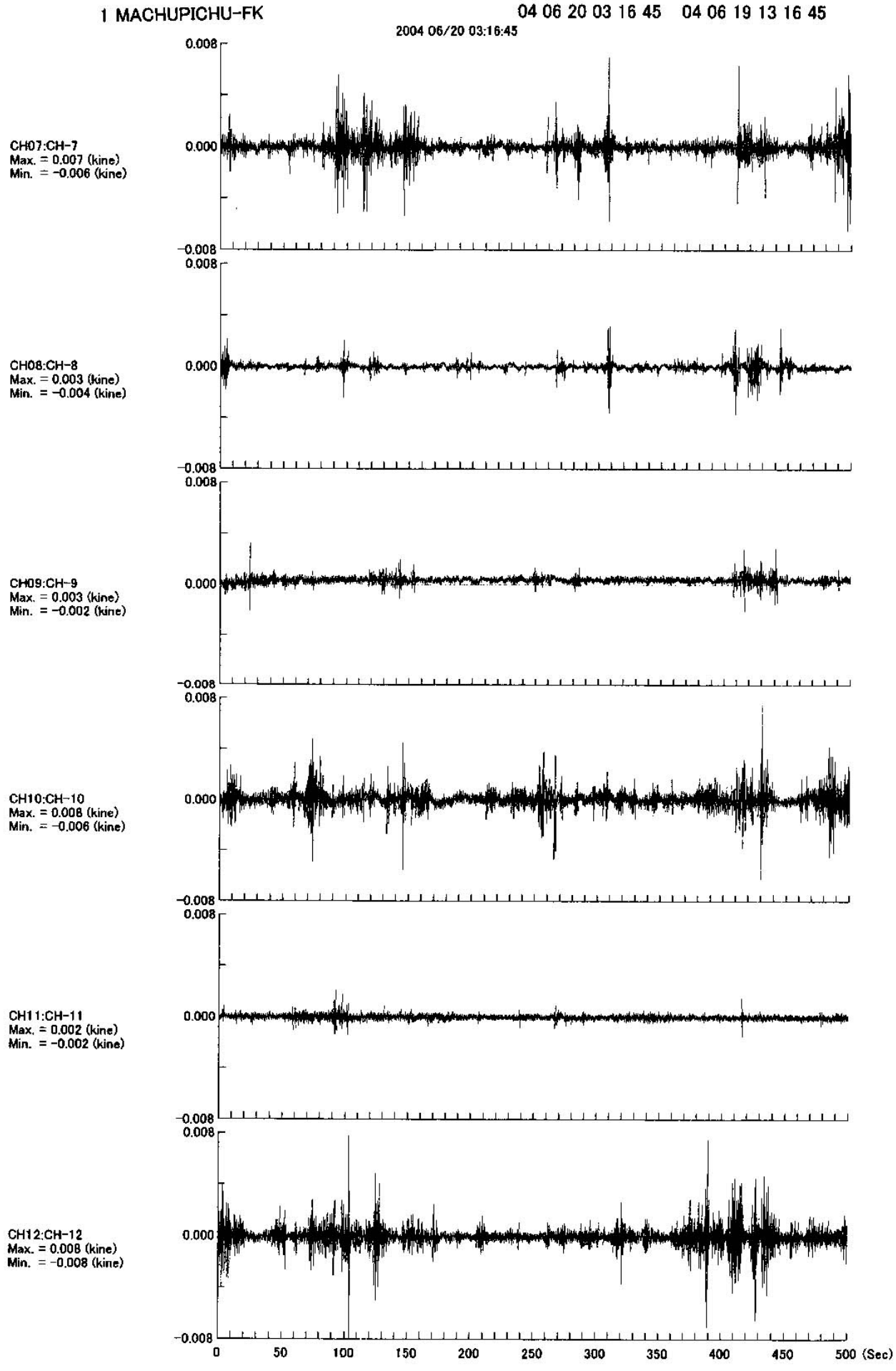
1. Measurements at Machupicchu Citadel

1.1. Plaza (square): Ground vibration measurement (vertical sensors)

At this site, measurements of the vertical components of the ground vibration were carried out. The sensors were laid in a triangular array system of 30 meter sides as shown in the figure below.

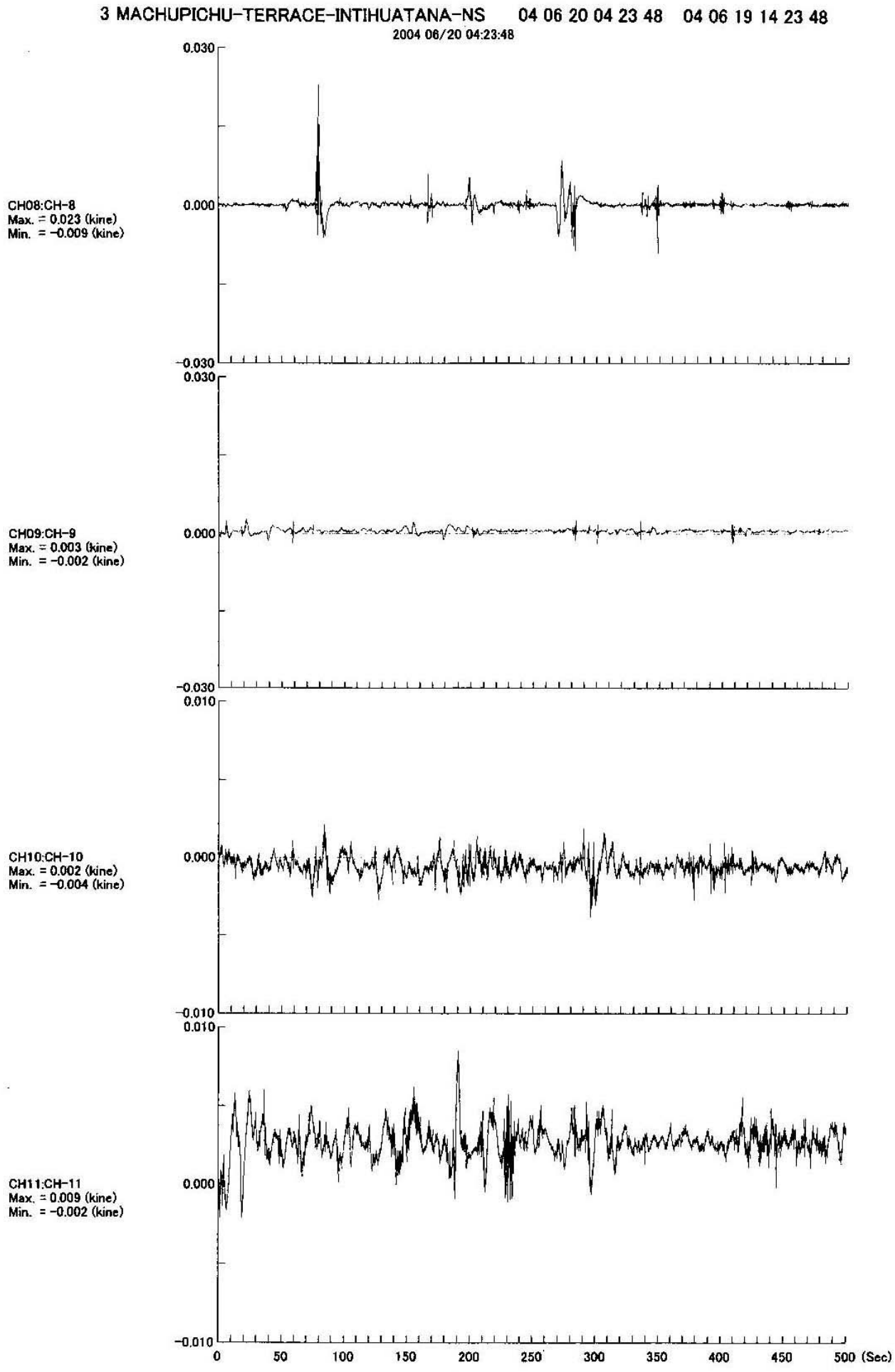


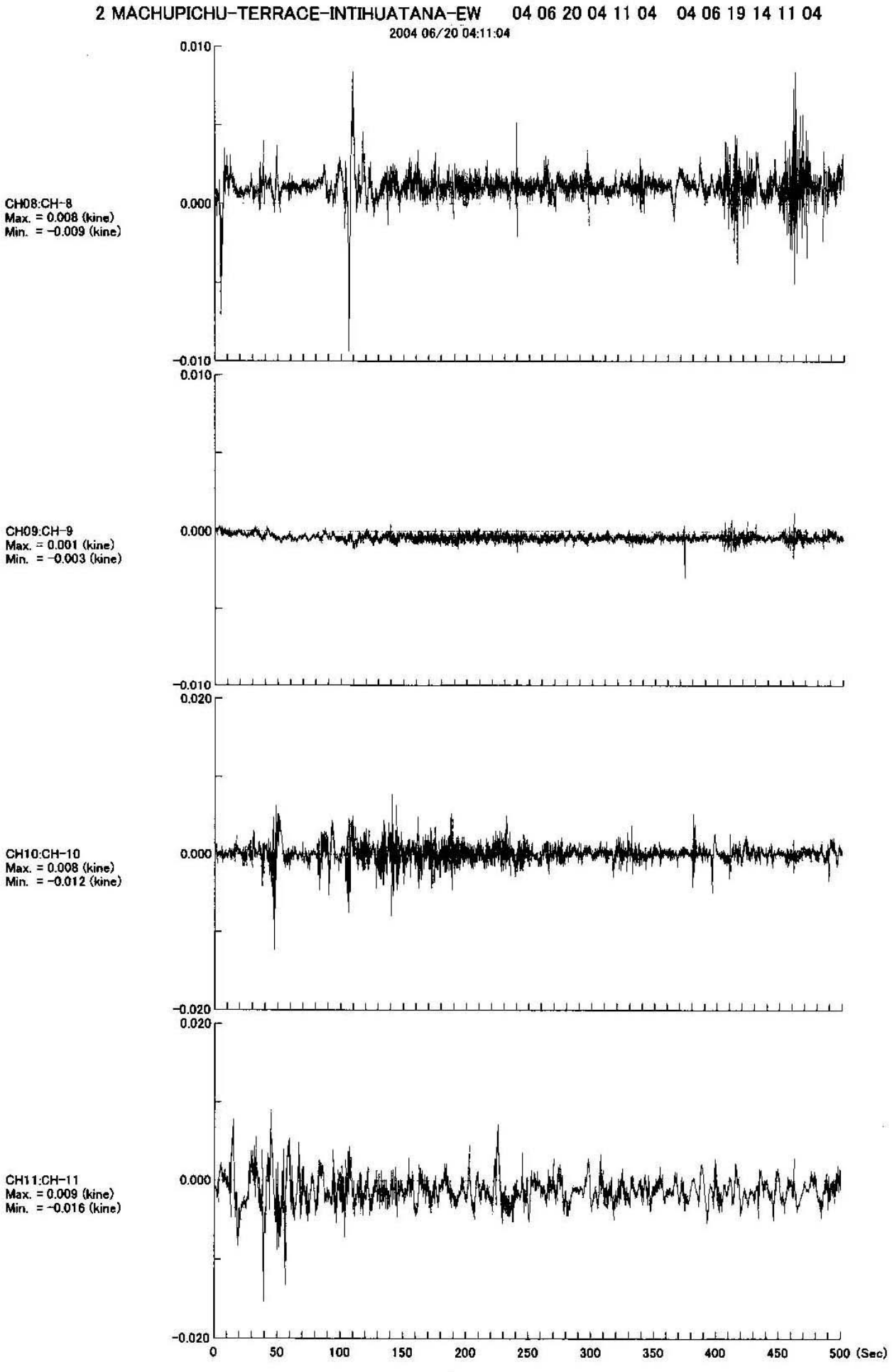
As may be noted, a sensor is located at centroid of the trapezoidal area. The array measurement is planned for F-K spectral analysis to obtain the characteristic Rayley wave dispersion curve, from which the shear wave velocity profile of the ground may be obtained by inverse analysis. The general trends of microtremor measurements are shown below:


1 MACHUPICHU-FK
04 06 20 03 16 45 04 06 19 13 16 45
2004 06/20 03:16:45
CH07:CH-7
Max. = 0.007 (kine)
Min. = -0.006 (kine)
CH08:CH-8
Max. = 0.003 (kine)
Min. = -0.004 (kine)
CH09:CH-9
Max. = 0.003 (kine)
Min. = -0.002 (kine)
CH10:CH-10
Max. = 0.008 (kine)
Min. = -0.006 (kine)
CH11:CH-11
Max. = 0.002 (kine)
Min. = -0.002 (kine)
CH12:CH-12
Max. = 0.008 (kine)
Min. = -0.008 (kine)
0.008
0.000
-0.008
0
50
100
150
200
250
300
350
400
450
500 (Sec)

1.2. Terraces of Intihuatana: Vibration of terraces structures (horizontal sensors)

In this case, horizontal components of the vibration of the terraces were measured. North-South (NS) direction and East-West (EW) direction were measured separately. Sensors were located at top, intermediate and lowest part of the terraces. Next figures show the result of measurements for NS and EW directions respectively:


3 MACHUPICHU-TERRACE-INTIHUATANA-NS 04 06 20 04 23 48 04 06 19 14 23 48
2004 06/20 04:23:48
CH08:CH-8
Max. = 0.023 (kine)
Min. = -0.009 (kine)
CH09:CH-9
Max. = 0.003 (kine)
Min. = -0.002 (kine)
CH10:CH-10
Max. = 0.002 (kine)
Min. = -0.004 (kine)
CH11:CH-11
Max. = 0.009 (kine)
Min. = -0.002 (kine)
0.030
0.000
-0.030
0.010
-0.010
0
50
100
150
200
250
300
350
400
450
500 (Sec)


2 MACHUPICHU-TERRACE-INTIHUATANA-EW 04 06 20 04 11 04 04 06 19 14 11 04
2004 06/20 04:11:04
CH08:CH-8
Max. = 0.008 (kine)
Min. = -0.009 (kine)
CH09:CH-9
Max. = 0.001 (kine)
Min. = -0.003 (kine)
CH10:CH-10
Max. = 0.008 (kine)
Min. = -0.012 (kine)
CH11:CH-11
Max. = 0.009 (kine)
Min. = -0.016 (kine)
0.010
0.000
-0.010
0.020
-0.020
0
50
100
150
200
250
300
350
400
450
500 (Sec)