Analysis of Positional Displacement in Bohol Island on Aftermath of the 2013 Central Visayas Earthquake from GNSS Surveys

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Key words: Deformation Measurement, GNSS, Reference System, Displacement

SUMMARY

A 7.2 magnitude earthquake struck Central Visayas, Philippines on 8:12 AM 15 October 2013. Ground shaking resulted in heavy casualties and damage to infrastructure and still linger threatened by failure-prone hillslopes, debris-filled rivers and collapsing sinkholes.

Quantifying the distribution of seismic-induced ground movement is important not only for assessing the damage caused by the earthquake but also for guiding local surveyors that the rely on a stable reference system for conduct of surveys in the area necessary for reconstruction and rehabilitation. A static GNSS survey was conducted from 10-12 November 2013 to quantify the displacements. GNSS receivers were occupied previously established High-Ordered reference points and fixing a relatively stable point.

Subsequently, the GNSS data were analyzed to assess the movement of areas were conducted. The average horizontal displacement is about 0.5166m+-0.2682m. Maximum displaced 1.169 m observed while minimum displacement is 0.063. The displacement headed towards southeast direction with greatest magnitudes computed at the northern and eastern portion of the Island. The results of the survey may provide key agencies further motivation to review the control points and conduct the necessary re-observation and re-adjustment.

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1. INTRODUCTION

A 7.2 magnitude earthquake struck Central Visayas, Philippines on 8:12 AM 15 October 2013. The National Disaster Risk Reduction and Management Council (NDRRMC) reported more than 222 deaths, 8 missing persons, more than 976 injured and more than 73,000 structures damaged including 10 iconic churches in Bohol and Cebu and estimated damage of US$52.06 million (NDRRMC, 2013).

Figure 1: Photograph of damaged Baclayon Church taken during the conduct of GNSS survey campaign.

The earthquake did not only affect the lives and infrastructure (e.g. roads, residential facilities and utitlities) of those living in the Central Visayas particularly Bohol Island but also its spatial infrastructure. One important component of this spatial infrastructure is the geodetic control network of the country. In the Philippines, the National Mapping and Resource Information Authority (NAMRIA) is the mandated agency to establish and maintain the geodetic control network in the country.

Global Navigation Satellite System (GNSS) Survey is an established technology and methodology that provide positioning and sensitive enough to measure movement and displacement of land.

The University of the Philippines Department of Geodetic Engineering (UP DGE) supported by the Department of Science and Technology (DOST) deployed a team of faculty and researchers to

Bohol Island a month after the event. The team conducted a campaign of static GNSS surveys and occupied previously established NAMRIA high-ordered control points to quantify and assess the movement of areas in the island.

2. SIGNIFICANCE

Quantifying the effect of seismic-induced ground movement was seen significant not only for assessing the physical damage but also to provide key agencies like NAMRIA motivation to review the stability and usefulness of the geodetic control network and guide local land surveyors that rely on a stable reference system for the conduct of surveys necessary to provide effective reconstruction and rehabilitation.

Since the campaign was done only within the Island of Bohol, it is recognized that the survey and its analysis may not result to the absolute displacement of occupied points but displacements relative to the control point set as the fixed point within the study area.

3. CHARACTERISTICS OF BOHOL AND THE 2013 BOHOL EARTHQUAKE

The province of Bohol is of composed of 75 islands and is part of the Central Visayas Region. The main island, the largest island contains Tagbilaran City, the capital of the province located southwest of the main island. The province is a tourist destination due to the diverse land formation and natural resources consisting of coral reefs and the hill system known as Chocolate Hills located near the town of Carmen. About 50% of the main island is covered by limestone.

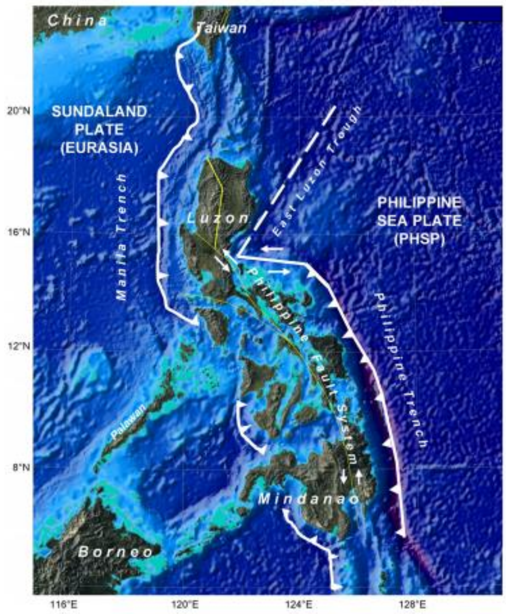
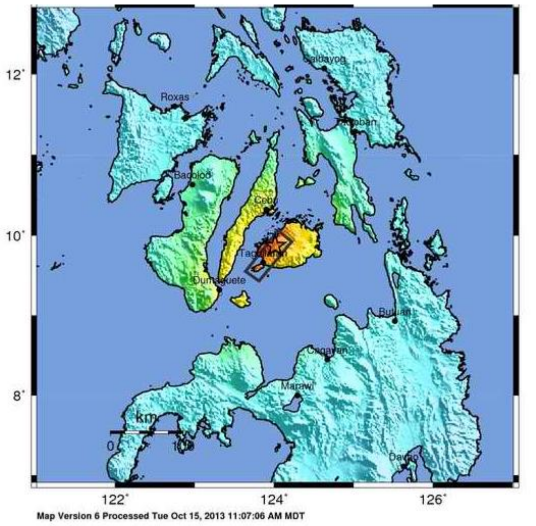


Figure 2: Map of the Philippines showing topography, bathymetry and major plates and fault systems (yellow lines) **(Galgana, et al., 2007)**

In

terms of geological characteristics, the Bohol island system is located between two opposing trench, the Manila Trench and the Philippine Sea Plate. It is also located west of the major Philippine fault system that traverses the major islands of Luzon, Visayas and Mindanao (Galgana, et al., 2007).

In terms of the number of major earthquakes, three are recorded in recent history. These are earthquakes that occurred in 08 February 1990, 15 October 2013 and 30 March 2015 with magnitudes 6.8, 7.2 and 4.7 respectively on the Richter scale.



PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Mod./Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<0.05	0.3	2.8	6.2	12	22	40	75	>139
PEAK VEL.(cm/s)	<0.02	0.1	1.4	4.7	9.6	20	41	86	>178
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

Scale based upon Worden et al. (2011)

Figure 3: Map showing the epicenter of the 2013 earthquake and affected areas **(Wikimedia Foundation Inc., 2015)**

According to the Philippine Institute of Volcanology and Seismology (PHIVOLCS) the 2013 earthquake's epicenter was located at 9^{o} 52' latitude and 124^{o} 04' longitude originating 12km deep from a previously unmapped reverse fault in the main island of Bohol (Anon., 2013).

The effect of the earthquake is characterized as violent to extreme violent with heavy to very heavy damage. This is coupled with the characteristic of Bohol Island as predominantly limestone material that produced sinkholes and failure prone hill slopes.

4. GLOBAL NAVIGATION SATELLITE SYSTEM (GNSS)

The advantage of the use of GNSS in positioning problem is observed since the country is within the region where most of existing satellite positioning systems are available. These are GPS, GLONASS, BEIDOU and QZSS. GPS or the Navigation Satellite Timing and Ranging Global Positioning System (NAVSTAR-GPS) was developed by the United States was the first fully functional satellite system used for military and commercial uses. GLONASS or GLObal'naya

Navigatsionnaya Sputnikovaya Sistema was developed and managed by the Russian Space Forces for the Russian Federation Government. BEIDOU or Beidou Satellite Navigation System (BDS) formerly COMPASS was developed by the Republic of China. Quazi Zenith Satellite System (QZSS) is maintained and operated by Japan Aerospace Exploration Agency (JAXA).

Differential GNSS technique is the commonly used to obtain high accuracy positioning. Static and rapid static methods are established methodologies used for geodetic and project control establishment. These require receivers to be placed on a point for several minutes and epoch rate is usually set at 15 seconds. Table 1 shows the duration for a static and rapid static surveys. The output of the process requires post processing to determine the corrected and adjusted positions of the unknown points.

Table 1. Typical Session Lengths for Static and Rapid Static Surveys (Ghilani & Wolf, 2008)

Method of Survey	Single Frequency	Dual Frequency
Static	30 min + 3min/km	20 min + 2min/km
Rapid Static	20 min + 2min/km	10 min + 1min/km

Analysis of fixed baseline measurement can be used in the analysis of the positional results to determine displacement. In this method, baseline observations are taken between fixed control stations and the observation results are compared to the previously established position of the fixed control stations (Ghilani, 2006).

5. NAMRIA GROUND CONTROL POINTS

The NAMRIA established first, second and third ordered ground control points within the whole Philippines using GNSS technology. Table 1 shows the standard accuracies adopted by NAMRIA and local surveyors. Establishment of these control points spanned from the early 1990s to the recent years. These control points were marked on the ground using standard materials and dimensions.

Table 2: The order and required accuracy for horizontal control establishment (DENR, 2007)

Order	Relative Error	Linear Error
First	1 is to 100,000	1 cm per km
Second	1 is to 50,000	2 cm per km
Third	1 is to 20,000	5 cm per km

In the Bohol group of islands, around 140 passive first, second and third ordered control points were established from different years. Figure 4 shows the plotted control points in the main island of Bohol.

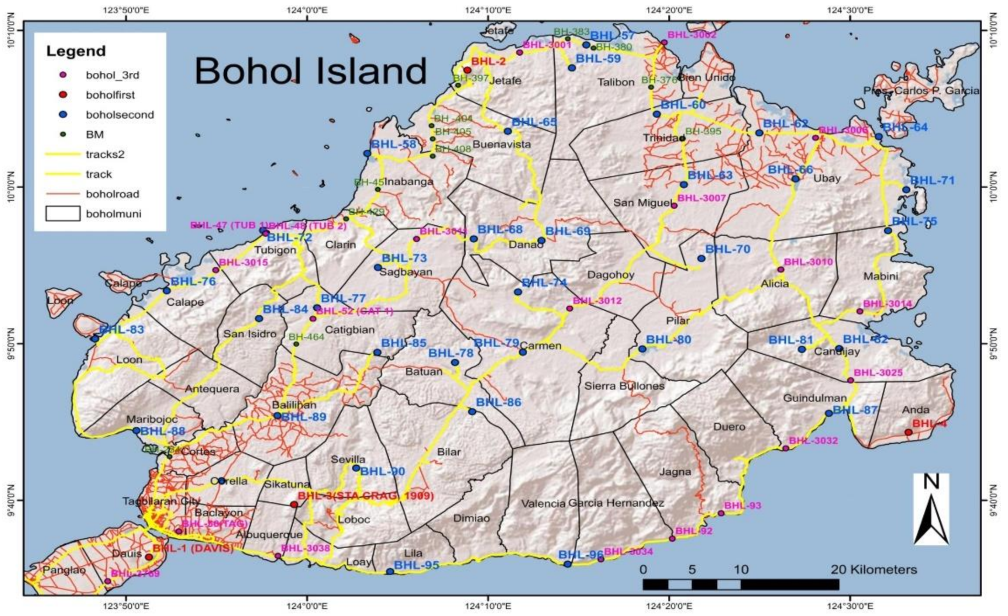


Figure 4: Map of Bohol Main Island with plotted NAMRIA 1st, 2nd and 3rd Ordered Ground Control Points

6. METHODOLOGY

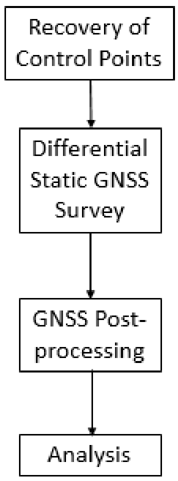


Figure 5: Methodology used in the conduct of displacement assessment using GNSS

Reconnaissance and control point recovery was done from 07 to 09 November 2013. From the 140 control points listed in the NAMRIA database, twenty-seven (27) horizontral control points of varying orders of accuracies were recovered on the ground. Figure 6 shows a sample recovered NAMRIA control point during reconnaissance. Figure 7 and Table 3 shows the location and list of recovered control points in the study area.

Figure 6: Typical NAMRIA ground control point recovered during the conduct of the GNSS campaign in Bohol.

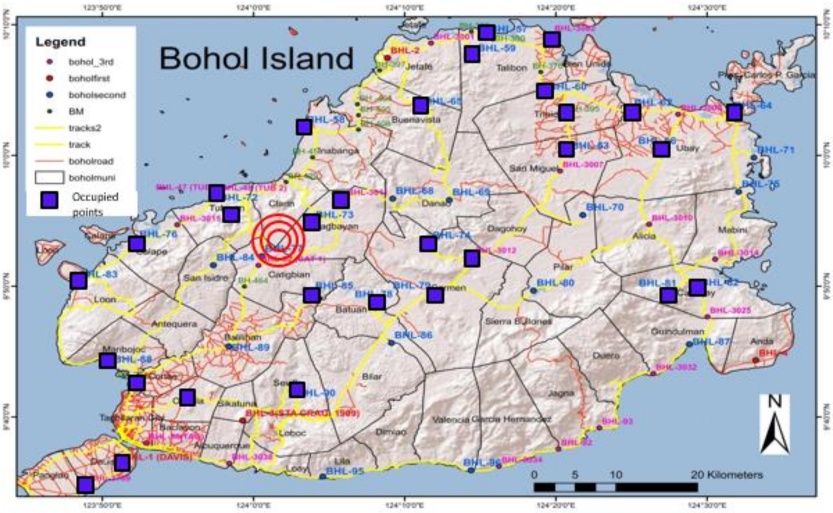


Figure 7: Map of Bohol with plotted recovered NAMRIA 1st and 2nd Ordered Ground Control Points and the approximate location of the epicenter of the 2013 earthquake.

Table 3: List of recovered NAMRIA control points with its geographic position in WGS84 and order of accuracy.

Point ID	Latitude (WGS84)	Longitude (WGS84)	Ellipsoidal Height	Horizontal/ Vertical	Order
BHL-1 (DAVIS)	9°36'22.44746"	123°51'15.91243"	247.564	HORIZONTAL	1
BHL-90	9°42'03.59074"	124°02'43.17725"	141.756	HORIZONTAL	2
BHL-63	10°00'09.39110"	124°20'48.71189"	80.873	HORIZONTAL	2
BHL-60	10°04'39.45850"	124°19'19.66871"	72.394	HORIZONTAL	2
BHL-57	10°09'04.81120"	124°15'25.59670"	77.318	HORIZONTAL	2
BHL-59	10°07'36.38022"	124°14'37.98280"	122.463	HORIZONTAL	2
BHL-62	10°03'27.40372"	124°24'59.17305"	72.639	HORIZONTAL	2
BHL-64	10°03'13.20626"	124°31'35.16843"	68.14	HORIZONTAL	2
BHL-66	10°00'31.27722"	124°26'59.19207"	95.028	HORIZONTAL	2
BHL-3002	10°09'13.90956"	124°19'44.26430"	70.106	HORIZONTAL	3
BHL-58	10°02'08.54469"	124°03'19.85079"	65.897	HORIZONTAL	2
BHL-65	10°03'33.65254"	124°11'05.61601"	192.782	HORIZONTAL	2
BHL-72	9°57'14.10713"	123°57'34.69615"	66.381	HORIZONTAL	2
BHL-73	9°54'51.66108"	124°03'55.16116"	303.683	HORIZONTAL	2
BHL-74	9°53'17.92671"	124°11'39.11687"	340.222	HORIZONTAL	2
BHL-76	9°53'22.68039"	123°52'15.25182"	65.522	HORIZONTAL	2
BHL-78	9°48'47.75428"	124°08'10.29452"	323.614	HORIZONTAL	2
BHL-79	9°49'27.17393"	124°11'55.48355"	282.187	HORIZONTAL	2
BHL-81	9°49'38.10047"	124°27'20.30332"	258.333	HORIZONTAL	2
BHL-82	9°49'41.19534"	124°29'23.55036"	69.744	HORIZONTAL	2
BHL-83	9°50'18.09153"	123°48'17.48435"	67.592	HORIZONTAL	2
BHL-94	9°41'14.73016"	123°55'16.87800"	129.088	HORIZONTAL	0
BHL-95	9°35'27.03717"	124°04'35.32705"	83.048	HORIZONTAL	2
BHL-3011	9°56'41.08833"	124°06'03.14955"	287.176	HORIZONTAL	3
BHL-3012	9°52'14.87995"	124°14'30.57770"	239.296	HORIZONTAL	3
BHL-85	9°49'26.43276"	124°03'53.39342"	297.647	HORIZONTAL	2
BHL-88	9°44'26.83881"	123°50'34.49469"	69.527	HORIZONTAL	2

Static GNSS survey was conducted occupying all the points. The critical task in this activity is the selection of the reference or fixed point from the list of control points and the logistics which include the limitation of the number of GNSS receivers, consideration on the available transport facility and travel time. The control point used as fixed point is BHL-01 located within the small island south-west of the main island in the Municipality of Davis. From BHL-01, BHL-90 and BHL-63 were connected and used as the base stations for the rest of the control points. Occupation time was set at one (1) hour per baseline. Five (5) dual frequency, multi-GNSS receivers were used in the conduct of the survey consisting of one (1) base receiver and four (4) independent roving receivers. The GNSS survey campaign was done from 10 to 12 November 2013. Figure 8 shows the differential static GNSS conducted and the baselines produced from the reference/ base stations.

GNSS post processing using third party processing software was done to process the baselines and obtain the position of the control points based on the survey and referred from BHL-01. The computed coordinates in geographic position were projected using the Universal Transverse

Mercator. Part of the results include the errors in the x and y direction and the baseline length. Accuracy assessment was done by computing the relative error.

Results were analysed using the method of fixed baseline measurement analysis. Displacements in terms of x and y component were computed together with the direction.

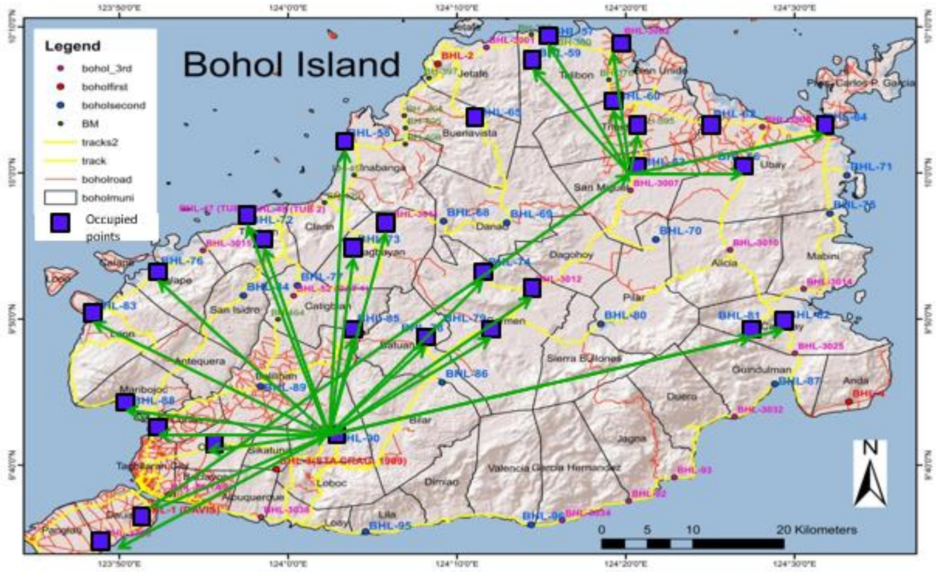


Figure 8: Differential Static GNSS survey campaign done from 10 to 12 November 2013.

7. RESULTS

Table 4: Assessment of precision per baseline.

Control Point	ΔX (m)	ΔY (m)	Resultant (m)	Baseline Length (m)	Precision Assessment
BHL-63 (base DAY 1	0.025	0.096	0.0992	69,559.45	1:701191
BHL-395	0.007	0.037	0.0377	5,425.56	1:144081
BHL-57	0.004	0.023	0.0233	19,165.18	1:820946
BHL-59	0.005	0.023	0.0235	17,774.84	1:755181
BHL-60	0.005	0.023	0.0235	8,728.31	1:370831
BHL-64	0.046	0.096	0.1065	20,478.65	1:192375
BHL-66	0.009	0.094	0.0944	11,301.83	1:119685
BHL-3002	0.006	0.046	0.0464	16,842.54	1:363067
BHL-58	0.011	0.047	0.0483	37,028.29	1:767107
BHL-65	0.015	0.044	0.0465	42,480.20	1:913817
BHL-72	0.008	0.013	0.0153	29,503.56	1:1932843
BHL-73	0.003	0.017	0.0173	23,693.89	1:1372550
BHL-74	0.016	0.057	0.0592	26,376.20	1:445521
BHL-76	0.005	0.022	0.0226	28,302.52	1:1254487
BHL-78	0.007	0.015	0.0166	15,921.01	1:961824
BHL-79	0.079	0.111	0.1362	21,653.78	1:158936
BHL-81	0.072	0.215	0.2267	47,127.22	1:207851
BHL-82	0.034	0.052	0.0621	50,752.81	1:816895
BHL-83	0.005	0.044	0.0443	30,436.50	1:687315
BHL-94	0.005	0.022	0.0226	13,683.93	1:606529
BHL-95	0.042	0.098	0.1066	12,651.57	1:118659
BHL-3011	0.003	0.014	0.0143	27,634.02	1:1930044
BHL-3012	0.061	0.122	0.1364	28,586.02	1:209575
BH-254	0.03	0.066	0.0725	18,891.94	1:260585
BHL-85	0.02	0.037	0.0421	13,769.65	1:327385
BHL-88	0.013	0.024	0.0273	22,636.87	1:829351
BHL-3769	0.047	0.118	0.1270	28,427.83	1:223813

Table 4 shows the assessment of precision done to determine the reliability of the results of the survey. It can be observed that values obtained are far greater than 1:100,000 which is the accuracy/ precision for First Order Geodetic Control.

Table 5 shows the computed positions of the control points from the observation as compared to the position based on NAMRIA database. Displacement in the x and y direction was computed by obtaining the difference between the observed position and NAMRIA data. The direction of the movement was also obtained by analyzing the signs of the difference. The magnitude of the displacement varies from point to point but it was observed that the minimum difference is at BHL-90 of 0.063 meters and at north-east direction. Maximum displacement was observed at BHL-58 at

1.169 meters and south-east direction. The average displacement is around 0.517 meters with a standard deviation of +-0.2682 meters.

Figure 9 shows the plotting of the displacement with direction. From the figure, it can be observed that greater displacement of the control points is at the north-east portion of the main island with a magnitude between 0.601 to 0.900 meters and a general direction of south-east. Control points nearer to the epicenter were observed to have smaller displacement between 0.101 to 0.600 but the direction greatly varies from each point.

Table 5: Results showing the position of the control points versus position from NAMRIA database and the computed displacement and direction.

Point ID	Observed Position			NAMRIA Database			Displacement			Direction	
	WGS84-UTM		EGM 2008	WGS84-UTM		EGM 2008	ΔX	ΔY	Resultant		
	Northing	Easting	Elevation (meters)	Northing	Easting	Elevation (meters)					
BHL-1 (DAVIS)	1061993.660	593754.449	184.055	1061993.660	593754.449	184.055	0	0	0.000	S	W
BHL-90	1072530.339	614672.410	77.103	1072530.291	614672.369	77.471	0.048	0.041	0.063	N	E
BHL-63	1106002.102	647622.567	16.019	1106002.326	647621.975	16.264	-0.224	0.592	0.633	S	E
BHL-60	1114287.606	644877.771	7.822	1114287.798	644877.159	7.796	-0.192	0.612	0.641	S	E
BHL-57	1122411.014	637720.456	12.762	1122411.173	637719.837	12.84	-0.159	0.619	0.639	S	E
BHL-59	1119688.928	636281.676	57.917	1119689.070	636281.051	58.04	-0.142	0.625	0.641	S	E
BHL-62	1112117.201	655223.395	7.188	1112117.428	655222.653	7.864	-0.227	0.742	0.776	S	E
BHL-64	1111735.066	667282.375	3.248	1111735.334	667281.678	3.408	-0.268	0.697	0.747	S	E
BHL-66	1106722.279	658901.433	29.558	1106722.532	658900.709	30.207	-0.253	0.724	0.767	S	E
BHL-3002	1122721.832	645592.388	1.693	1122721.996	645591.585	5.395	-0.164	0.803	0.820	S	E
BHL-58	1109545.087	615673.791	1.082	1109546.059	615673.141	2.109	-0.972	0.65	1.169	S	E
BHL-65	1112208.648	629844.735	128.218	1112208.755	629844.104	128.58	-0.107	0.631	0.640	S	E
BHL-72	1100469.218	605191.946	1.763	1100469.864	605191.434	2.701	-0.646	0.512	0.824	S	E
BHL-73	1096129.295	616791.335	240.313	1096129.743	616791.384	239.478	-0.448	-0.049	0.451	S	E
BHL-74	1093298.378	630932.561	275.511	1093298.369	630932.288	275.772	0.009	0.273	0.273	N	E
BHL-76	1093334.408	595483.262	1.525	1093334.658	595482.603	2.022	-0.25	0.659	0.705	S	E
BHL-78	1084977.099	624599.987	258.665	1084977.119	624599.822	259.06	-0.02	0.165	0.166	S	E
BHL-79	1086211.847	631456.402	217.321	1086211.847	631456.204	217.613	0	0.198	0.198	S	E
BHL-81	1086658.624	659632.024	193.429	1086658.908	659631.408	193.835	-0.284	0.616	0.678	S	E
BHL-82	1086770.160	663386.630	4.862	1086770.466	663386.160	5.413	-0.306	0.47	0.561	S	E
BHL-83	1087646.912	588255.182	4.204	1087646.875	588254.683	4.263	0.037	0.499	0.500	N	E
BHL-94	1070990.309	601075.418	64.872	1070990.185	601075.516	65.236	0.124	-0.098	0.158	N	E
BHL-95	1060360.033	618128.686	19.099	1060360.178	618128.550	19.349	-0.145	0.136	0.199	S	E
BHL-3011	1099503.725	620678.716	222.332	1099503.745	620678.298	222.989	-0.02	0.418	0.418	S	E
BHL-3012	1091380.676	636162.531	171.676	1091380.723	636162.198	174.781	-0.047	0.333	0.336	S	E
BHL-63	1106002.159	647622.625	15.658	1106002.326	647621.975	16.264	-0.167	0.65	0.671	S	E
BHL-85	1086139.358	616769.510	233.015	1086139.573	616769.372	233.242	-0.215	0.138	0.255	S	E
BHL-88	1076868.082	592455.030	5.803	1076868.452	592455.159	5.947	-0.37	-0.129	0.392	S	E

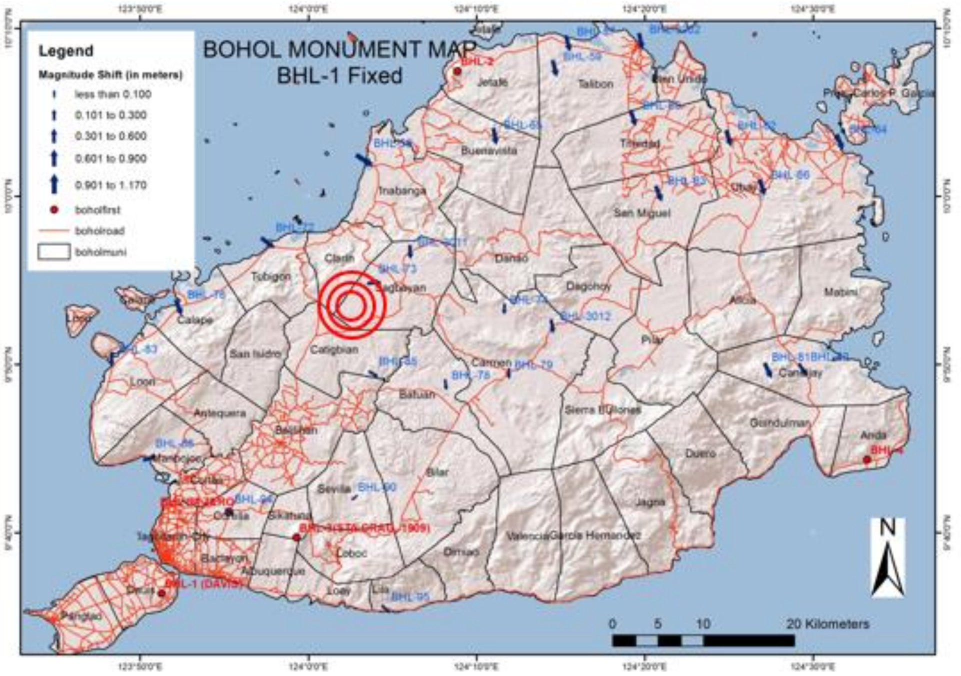


Figure 9: Plotting of the displacement with direction

Although the elevations of the points in EGM2008 were determined. Analysis of these values were not included since EGM2008 is not 100% fit with the vertical datum of the country. The comparison of elevation between the observation and NAMRIA database maybe doubtful.

8. CONCLUSIONS AND RECOMMENDATIONS

It was observed from the result of the research that all the points moved from 0.06 meters to more than 1 meter majority of which are in the south-east direction. It can therefore the concluded that the stability and usefulness of these points as references for geodetic surveys are already compromised. It is therefore recommended that the mandated agency such as NAMRIA re-occupy these points and provide an updated solution of position.

However, the movements are based on the initial assumption that BHL-01 is fixed therefore the computed displacement is relative to this control point. Because of this, movement of BHL-01 was not measured and assessed. It is recommended that in doing similar activities in the future, selection of fixed point be done considering the geology and better stability of the location. From Figure 2 it can be observed that Palawan Island maybe the best location to have surveys referenced from, since this island is relatively far from the major fault lines in the Philippines.

Finally, since majority of NAMRIA control points are passive control points, it is recommended that a similar static GNSS campaign be done in the provincial level at least once a year initiated by NAMRIA with coordination from local surveyors headed by the Geodetic Engineers of the

Philippines. This may provide historical data regarding movement and magnitude of the movement using the control points which the agency may not have.

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BIOGRAPHICAL NOTES

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